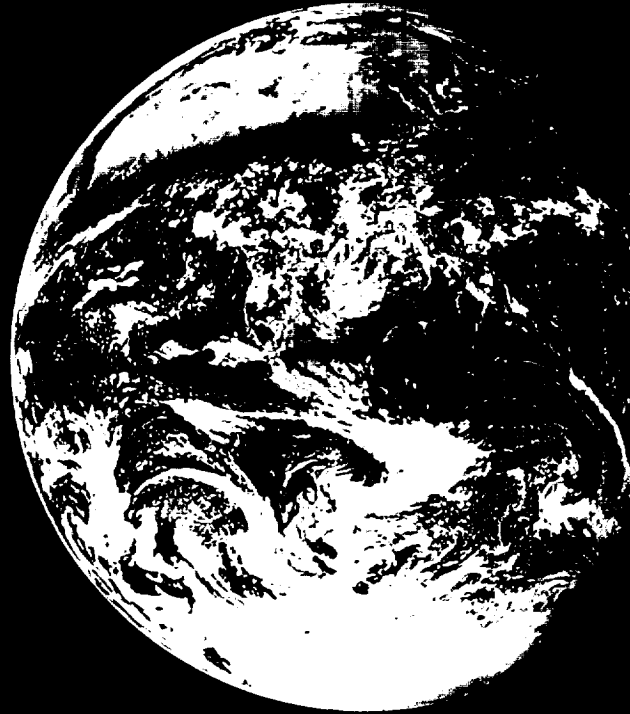


EXOBIOLGY IN EARTH ORBIT

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EXO BIOLOGY IN EARTH ORBIT

The Results of Science Workshops Held
at NASA Ames Research Center

Edited by

D. DeFrees, D. Brownlee, J. Tarter,
D. Usher, W. Irvine, and H. Klein

Prepared at Ames Research Center



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Foreword

One might think that the origin of life is strictly a biological question, to be attacked by experiments in Earth-based laboratories. That is largely true. But the chemical processes that operated over the eons of remote geological time to produce the first reproducing organisms occurred in the terrestrial environment of that time—and that environment was established by the processes that led to the formation and chemical evolution of the Earth itself. The traces of such processes to be found on the Earth today are studied by Earth scientists, and there is much to be learned of relevance to the origin of life.

But the Earth did not spring from nothing; it was formed at the same time as the Sun, the planets, and small bodies of the Solar System about 4.5 billion years ago from primitive material in interstellar space. At least the relative abundances of the chemical elements, probably the chemical compounds into which they were combined, and perhaps the detailed physical properties of the pre-Earth material, were established by processes taking place in space before the Earth was formed. At least in principle, then, those who study space have insights to contribute.

Exobiology, the study of processes relevant to biology that are occurring in space, is becoming a mature field. One immediately thinks of experiments to detect life elsewhere, like the Viking experiments at Mars and searches for radio signals from life elsewhere. Indeed, such studies have been undertaken by NASA's Life Sciences Program. But they are only the most visible elements of a much broader program to uncover phenomena relevant to the origin and evolution of life throughout the universe. Astronomical studies reveal that the abundances of the elements in space seem to be very similar throughout our galaxy. Our Sun fits the general pattern because it and the other stars are so massive that as they form, they gravitationally draw in all types of material without regard to differences in chemical or physical properties. But on-site studies of the planets and satellites of the Solar System—including the Earth—show large variations that can be interpreted in terms of different chemical and physical processes occurring in the solar nebula of gas and dust before the planets formed. The fate of carbon at different places in the solar nebula is an example, and one of great importance for the origin of life.

In interstellar space, carbon takes a variety of forms. In the dense “molecular clouds” from which stars (and presumably planets) are forming at the present

epoch, most of the carbon is observed to take the form either of carbon monoxide or of solid material in microscopic dust grains. Some of the grains may be made of graphite, while others appear to contain relatively heavy organic molecules, rather like those forming the organic residue in carbonaceous meteorites that have been recovered after they have fallen to the Earth's surface, and analysed in the laboratory. How did carbon become part of the Earth? Clearly not as a gas like methane or carbon monoxide, as it is known that the noble gases of even greater molecular weight are enormously depleted relative to their abundances elsewhere. It is more likely that at the time the Earth formed the local temperature and pressure favored the retention of carbon in solid form, possibly in the form of the heavy organic molecules like those in meteorites. Such a hypothesis raises questions open to further study: Were the organics simply those astronomers infer to be part of interstellar dust? Did they survive the heating believed to have accompanied the formation of the Solar System? If so, how? Can such primitive materials be observed at the current epoch, perhaps in comets?

All these questions are interesting, and many of them can be addressed using the techniques of space research. Infrared telescopes in Earth orbit, like the projected Space Infrared Telescope Facility (SIRTF) and Infrared Space Observatory (ISO), can make more definitive studies of the carbon in molecules and solids in interstellar molecular clouds. They and the Hubble Space Telescope (HST) can provide more accurate information about asteroids thought to be representative of the bodies where carbonaceous meteorites originate. High-flying aircraft can recover interplanetary particles, some of which could be fragments of comets. And a rendezvous mission to a comet, such as the Comet Rendezvous Asteroid Flyby (CRAF), could yield far more information about comets, of which the Comet Halley flyby missions gave tantalizing hints.

This volume gives a status report on the scientific investigations which can be undertaken in the field of exobiology using instruments in Earth orbit. The reader will find that there is much to be done and a whole host of questions that can be addressed. Every scientist interested in exobiology should consider how his or her work will be affected by the opportunities described here. They should also see what they can do to assist the Nation to reestablish a first-class space-science program, given the constraints imposed by the aftermath of the Challenger accident.

George Field
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Preface

The Science Workshops on Exobiology in Earth Orbit were held to thoroughly explore all concepts for scientific experiments of exobiological interest to be carried out on any type of Earth-orbiting spacecraft over the next few decades and to make recommendations on which classes of experiments should be carried out. The Workshops grew out of the realization that many new opportunities would become available to exobiology before the end of this century. Furthermore, three series of workshops redefining the scope of the field of exobiology had just concluded. (The results of these workshops are published in three NASA Special Publications, SP-476, SP-477, and SP-478, listed at the end of Chapter 1.) It was thus an opportune time to connect the basic science objectives defined by these three efforts to the spaceflight missions that were being contemplated for the remainder of this century and that could be used to realize the science objectives. The primary focus was on missions sponsored by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Necessarily, only those opportunities which were known at the time of the Workshop meetings were considered; subsequent missions were omitted not because of lack of interest, but rather because we were not aware of them. The January 1986 Challenger accident has led to uncertainty in the timetables for the various Earth-orbital missions discussed in this report, and in some cases to the vehicle that will be used to launch them. This must be kept in mind; while the basic scientific objectives and plans described in this report are still valid, the specifics of their implementation are subject to change.

The Workshops on Exobiology in Earth Orbit should be viewed as the second step of a three-part process, each step of which increases the number of people who are thinking about the role of Earth-orbital space missions in the field of exobiology. The first step was a series of informal meetings held at NASA's Ames Research Center during 1982-83 that included primarily Ames investigators. The Workshops on Exobiology in Earth Orbit, the second step of the process, was composed of about 40 scientists from around the world, including astronomers, chemists, biologists, and geologists; the recommendations for experiments, summarized in Chapter 6, represent the consensus opinion of this particular group of experts. The third step in the process begins with the distribution of this report. All interested scientists can now consider the classes of

experiments recommended by the Workshops, discuss their merits, and formulate their own ideas for experiments to be carried out in Earth orbit. The recommendations of these Workshops should not be viewed as final, but rather as a starting point for further discussions within the general scientific community. If exobiologists are inspired to give serious consideration to performing experiments in Earth orbit, and if nonexobiologists are inspired to look at their work from a new point of view, then these Workshops will have succeeded.

The scientists who provided their time and expertise, attended the meetings, discussed the ideas, and who did the thinking, the writing, and the rewriting are listed at the end of this Preface. It is they who are responsible for the content of this report. The chairpersons of the Workshops were Harold P. Klein from Santa Clara University and William M. Irvine from the University of Massachusetts. Three science working groups were formed reflecting the basic nature of exobiological investigation, which includes observation, collection, and simulation. These were led by Jill Tarter from the University of California at Berkeley and the SETI Institute (Observational Exobiology), Don Brownlee of the University of Washington (Cosmic Dust Collection), and David Usher from Cornell University (*In Situ* Experiments). John Billingham of NASA Ames provided the principal liaison between the Workshops and the Ames Research Center. The Workshops members benefited from many experts who came to the meetings and gave tutorials on specific aspects of Exobiology in Earth Orbit. They are:

- Roger Arno, NASA Ames Research Center (spacecraft opportunities)
- Martin Barmatz, Jet Propulsion Laboratory (containerless processing)
- Peter Banks, Stanford University (Space Station)
- Bill Berry, NASA Ames Research Center (spacecraft opportunities)
- Don Brownlee, University of Washington (cosmic dust)
- Ted Bunch, NASA Ames Research Center (cosmic dust collection)
- Graham Cairnes-Smith, Glasgow University (origin of life)
- Sherwood Chang, NASA Ames Research Center (cosmic history of the biogenic elements and compounds)
- Martin Cohen, University of California at Berkeley (proto-planetary systems)
- Robert Davies, University of Pennsylvania (panspermia)
- Don DeVincenzi, NASA Headquarters (exobiology)
- Mike Duke, NASA Johnson Space Center (lunar bases)
- Mayo Greenberg, University of Leiden (bacterial survival in grains)
- Gerda Horneck, Institut für Flugmedizen, Koln, West Germany (microbial survival in space; ESA activities)
- William Kinard, NASA Langley Research Center (Long-Duration Exposure Facility)
- Michael Lampton, University of California at Berkeley (the space environment)

Joseph Nuth, NASA Goddard Spaceflight Center (small-particle nucleation)
Jeff Scargle, NASA Ames Research Center (planetary detection)
Jill Tarter, University of California at Berkeley and SETI Institute (observational opportunities)
Chandra Wickramasinghe, University College, Cardiff (panspermia)

We are indebted to all of these people for their time and effort. Additional thanks are due to Bill Berry and Mike Duke who contributed written summaries of their tutorials that are included in Chapter 2 of this report. The many logistical details that go along with running meetings which exceed 50 attendees, all of whom need to be housed, fed, reimbursed, and aided in a myriad of ways, were efficiently handled by Wanda Davis from the Molecular Research Institute. We also owe special thanks to Vera Buescher and Elyse Murray of the SETI Institute who provided invaluable assistance. Finally, we thank Guy Fogelman of RCA Government Services for reading the full manuscript.

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Executive Summary

One of the principal products of these Workshops is the list of experiments which the members recommend and which is summarized in Chapter 6. A brief list of these recommended experiments is given here. Those listed for the Observational Exobiology section are in order of decreasing priority as determined by a consensus of the Workshop members. Otherwise, no priorities are implied by the order in which the experiments are listed.

Observational Exobiology

1. Search for extrasolar planetary systems
2. Study star-forming regions in the galaxy—analogs for the solar nebula
3. Study comets, asteroids, Titan, and the giant planets in our own solar system
4. Study the organic chemistry of interstellar molecular clouds

Cosmic Dust Collection

1. Develop and implement capture techniques which preserve biogenic material
2. Develop and implement techniques to determine the orbits of dust particles
3. Refine laboratory methods for the analysis of small particles

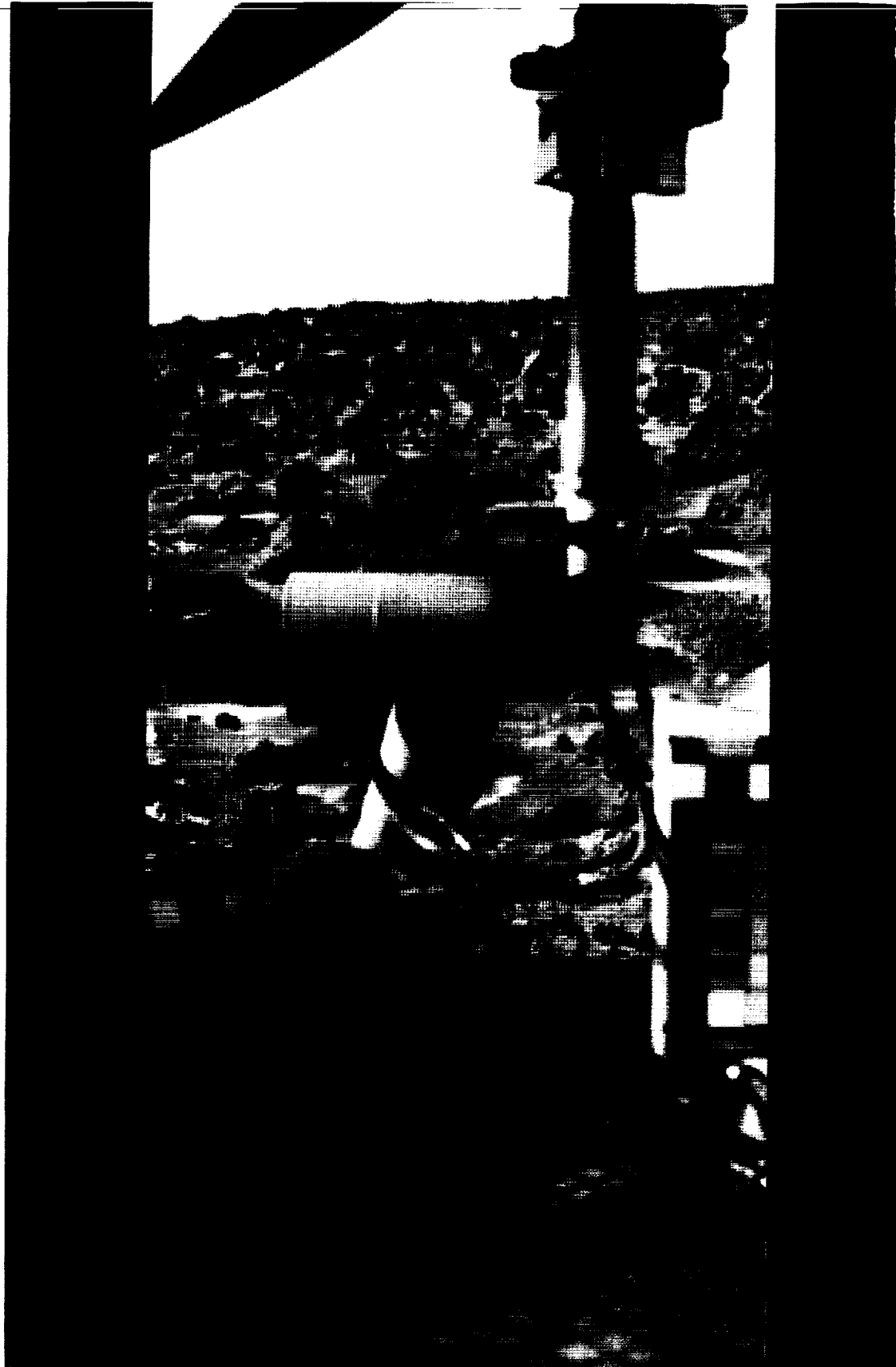
In Situ Experiments

1. Study the formation, condensation, aggregation, and surface chemistry of suspended dust grains
2. Create, release, and monitor an artificial comet in space
3. Determine the viability of microorganisms in space

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Chapter I

Biology and the Space Sciences

H. P. Klein

It became more and more apparent, as data from the two Viking landers on Mars began to accumulate during 1976 and 1977, that Mars is an inhospitable planet for life. The excitement generated by initial, presumptive indications of metabolic activity gave way under subsequent experimentation, both on the Martian surface and in ground-based laboratories, to the realization that simple, unanticipated, physico-chemical rather than biological processes were probably the basis for the observed phenomena. To many this signaled an attenuation, if not the end, of interest by biologists in conducting research in the space sciences. From time to time "exobiology," i.e., the study of extraterrestrial organisms, has been referred to as "an endeavor to study that which is nonexistent," and the Viking results seemed to end any hope of studying the biota of another planet. The conclusion was drawn, by some, that biologists involved with such matters would now withdraw from participation in space exploration and redirect their efforts to terrestrial biology.

Proponents of this view were mistaken, however, because they did not understand the biological context within which the search for life on Mars was carried out. For the biologist, the Viking mission was an important test of ideas about how life arises from relatively simple nonbiological materials. These ideas have as their central theme the concept that living systems arise through a process of chemical evolution, a process in which molecules of increasing complexity are produced under the influence of natural energy sources until a stable, self-reproducing system is established. According to this view, simple compounds containing the "biogenic" elements—carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus—condense under appropriate conditions to form the direct precursors of living matter, ultimately resulting, with further chemical modifications, in replicating organisms.

Once it became clear that direct analysis of other objects in the solar system would become feasible through the use of spacecraft technology, attention

The Martian surface, as seen by the Viking lander.

naturally turned to Mars as the most accessible, “Earth-like” extraterrestrial object upon which to test this theory of chemical evolution. Before the Viking mission it was assumed that organic materials, produced either photochemically from the Martian atmospheric components or derived from meteoritic infall from the neighboring asteroid belt, would be present on the Martian surface. Indeed, one of the key objectives at that time was to ascertain the level of complexity of these putative organic compounds. Did they include organics related to terrestrial biological matter? Had chemical evolution on Mars advanced to the point of producing replicating molecules? To biologists the search for life on Mars was characterized by these and related questions, and not solely by a quest for evidence of living or fossil “Martians.” In retrospect, the Viking results underscored how naive our assumptions were about the ease with which replicating organic systems are formed and evolve on a planetary body. The results emphasize how much additional knowledge we need about chemical and biological evolution.

These uncertainties, of course, are applicable when contemplating the origins of life on our own planet. The answers to many of the key questions in our scenario of chemical evolution still elude us. How and where did the carbon-containing precursors of terrestrial biology arise? What contributions to the inventory of such precursors were made by comets, asteroids, or cosmic dust during or after the accretion of the Earth? Indeed, what is the history of the biogenic elements themselves? Can we trace their origins and subsequent interactions back through pre-solar system epochs to cosmic dust and interstellar gases? During the past three decades, considerable strides have been made by chemists and biochemists in demonstrating the relative ease with which the biogenic elements can condense to form complex, biologically important organic compounds. However, we are on tenuous ground when we try to pin down these chemical processes in time and space. How much of the process took place on this planet? What relationships exist between the organic compounds found in the interstellar medium and those found in meteorites, comets, other solar system objects, and the Earth?

The open issues regarding the accumulation of the organic material that set the stage for the appearance of replicating molecules on Earth are further obscured because our models for the early Earth preceding and during the period when organic chemical evolution “went critical” (i.e., gave rise to reproducing chemicals) are relatively imprecise. Not only is it important to understand the physical environment within which replicating systems first appeared, but such knowledge is equally necessary to gain insight into the earliest stages of biological evolution—that is, how life, once initiated on Earth, was sustained and became diversified. Uncertainties exist in specifying the history of the terrestrial atmosphere. How, and over what time span, did the Earth’s volatiles accumulate? Was the atmosphere strongly reducing or more oxidized at various stages in

the process? Just what is the detailed history of molecular oxygen as a component of the Earth's atmosphere? For our models of the prebiological era on Earth, what are we to assume to be the history of the flux of solar (and other?) radiations reaching the surface? What is the possible significance of large-body impacts with the Earth during some or all of this phase of evolution?

From the foregoing discussion, it should be clear that the intellectual content in the field of exobiology goes far beyond attempts to detect life on another planet. Thus, while exobiology has historically been narrowly viewed as the search for extraterrestrial life, in point of fact, the field today is better described as an interdisciplinary science devoted to the study of evolutionary biology. As such, it encompasses the origins and history of the major elements required for life; their processing in the interstellar medium and in protostellar systems; their incorporation into organic compounds on the primitive Earth and on other celestial objects; the interactions of an evolving planet with the evolution of complex organic compounds; the conditions under which chemical evolution resulted in replicating molecules; and the subsequent interactions between an evolving biota and further planetary evolution. To implement the objectives of this discipline, investigators in the field are studying different aspects of the evolutionary process in order to synthesize from these studies a plausible "road map" that leads from the origin of the universe to the establishment of a sustained biota on Earth. It is reasonable to expect that biologists will acquire new and important information in the future from ground-based studies of terrestrial and extraterrestrial materials, as well as from laboratory demonstrations of critical chemical and biochemical pathways involved in chemical evolution. Moreover, one can readily assume that telescopic probing of the solar system and beyond by physical scientists will provide fresh insights into many of these issues. However, successful implementation of the broad program of inquiry that constitutes modern exobiology requires that biologists interact directly with astronomers, astrophysicists, atmospheric chemists, geochemists, and other physical scientists in order to resolve many of the open questions in this field. In this regard, the opportunities provided by space technology are especially intriguing. Direct measurements of the compositions of the atmospheres and/or surfaces of objects such as comets, Jupiter, Titan, Saturn, Neptune, and Uranus—all of which are known to contain at least simple organic molecules—and investigations of the chemistry of carbonaceous asteroids, can provide valuable insights into the nature of organic chemical evolution within the solar system. Detailed analysis of solar system objects, particularly the Moon and Mars, including careful assessment of their cratering histories, could advance our understanding not only of the early history of the solar system during the prebiological era on Earth, but also of later epochs throughout biological evolution.

With the various space missions now under development and on the drawing boards, both in the United States and abroad, it is clear that much progress is to be expected in exobiological science. It thus seemed important to study the extent to which Earth-orbiting space missions, such as the Space Station, might make useful contributions. *A priori*, it would appear attractive to utilize such permanently orbiting facilities to observe a wide range of objects, from interstellar clouds to solar system bodies; to collect cosmic materials for subsequent analysis; and to conduct *in situ* experiments, taking advantage of the natural environment of space. The subsequent sections of this publication are devoted to a critical examination of these possibilities, as well as to a consideration of other ways in which they could provide definitive insights for exobiological science.

Suggestions for Further Reading

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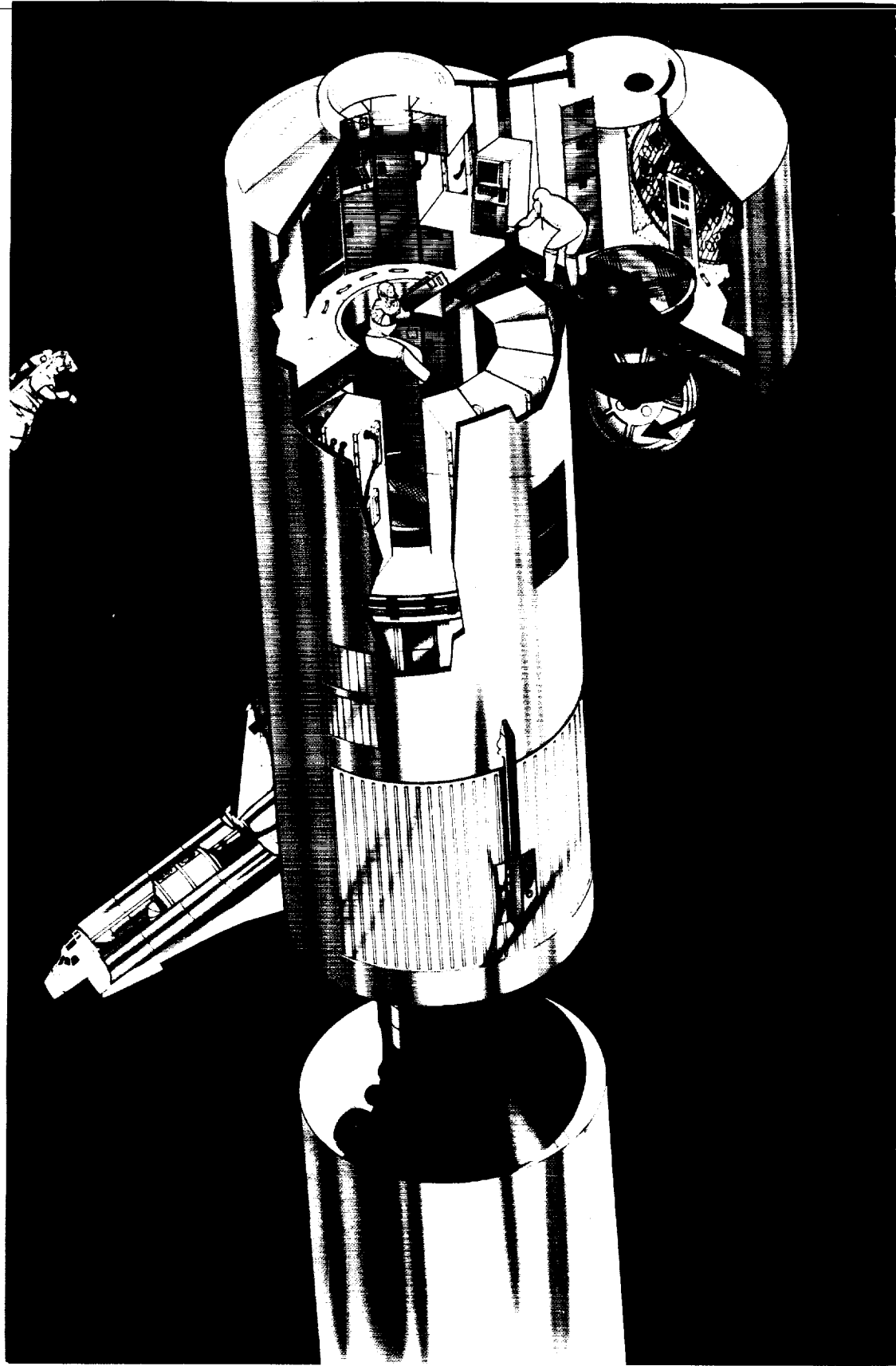
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Chapter II

Observational and Experimental Opportunities in Earth Orbit

W. Berry, M. Duke and J. Tarter

As a prelude to the discussion of scientific questions and the Earth-orbital investigations that can be applied to answer them, it is appropriate to briefly describe the Earth-orbital opportunities available to the exobiologist. These have been limited to those projects which are already proposed and which have some probability of going into operation before the end of this century. An exception, the lunar base, which may be operating in the first to second decade of the 21st century, has been included as it has particularly intriguing possibilities for exobiological investigations. There are five classes of Earth-orbital flight opportunities: Space Shuttle (Space Transportation System (STS)) laboratories, spacecraft deployed from the Shuttle, spacecraft deployed from expendable launch vehicles (ELVs), the Space Station, and lunar bases.

2.1 Free-Flying Spacecraft and the Space Shuttle

The ELV^a program provides access to a variety of orbital inclinations and altitudes. (Until the Shuttle is operational out of Vandenberg Air Force Base, California, these vehicles offer the only means of reaching orbits of greater than 57° inclination, such as polar and sun-synchronous orbits.) Current U.S. civil ELVs can insert from 200 kg into low Earth orbit with the Scout, to 2000 kg into the higher-energy geostationary orbit with the Atlas-Centaur. NASA manages payload launches with these ELVs and with the intermediate capability Delta and Atlas-F systems. Commercial firms are also marketing launch services with the expendable vehicles which supplement NASA's ELV capability. The

^aA complete list of abbreviations is included in Appendix A.

An Artist's concept of the Space Station in Earth orbit

Air-Force-managed Titan 34D (which can insert 5000 kg into geostationary orbit), the French-managed Ariane, and the U.S.S.R. Proton ELVs are also potential launch vehicles.

The Space Shuttle can reach an altitude of 600 km with a payload the mass of the Space Telescope (11,600 kg) and will be able to reach more than twice this altitude if plans go forward to add additional Orbital Maneuvering System kits. The Shuttle will be able to carry 30,000 kg to a 400-km orbit and half this into a polar orbit when the western launch site (Vandenberg) begins supporting launches. A variety of payloads can be carried and either retained aboard the Shuttle during the mission or deployed into space or into Earth orbit. If retained, the payload will be functional only during the 7-day period typical of orbital operations. Small payloads may be flown as payloads of opportunity in the Shuttle cargo bay as "getaway specials" (GAS) or as part of the Hitchhiker program on the orbiter mid-deck, provided that they have minimal resource needs. More complex and/or larger payloads fly in the 60- by 15-foot Shuttle cargo bay as part of a Spacelab manifest, either inside Spacelab or exposed to space on a pallet. Either configuration has access to the extensive services provided by Spacelab, such as communications, fluid loops, and control panels. More complex, and likely more costly, independent payloads using a portion or all of the bay can also be considered; these could be extended beyond the bay once orbit is attained.

Spacecraft deployed from the Shuttle provide long exposures, flexibility in orbit selection, and the possibility for retrieval. These payloads can be visited periodically by the Shuttle for servicing, retrieval and replacement of experiment packages, and recovery for return to Earth. Another option would be to share a spacecraft performing another primary task; this option relies on an already approved mission which would not be compromised by the addition of an exobiology experiment. Drawbacks to this approach are that the orbit, altitude, resource availability, etc., are dictated by the host.

Greater flexibility is provided by sharing accommodations on a spacecraft designed to support multiple tasks, in that the accepted payloads are roughly equal in priority; such spacecraft will be available in the near term. In order of increasing capability they include NASA's Long Duration Exposure Facility (LDEF), Spartan, and the European Retrievable Carrier (EURECA). LDEF will be flown in a series of missions providing exposure to space for a number of self-contained experiments; i.e., the spacecraft does not provide power, propulsion, communication, or pointing. (LDEF I was deployed in April 1984 and because of the Challenger accident has yet to be retrieved.) After exposure to the space environment for a period of up to several years, LDEF is retrieved by the Shuttle and returned to the ground for experiment evaluation. NASA's Spartan is an autonomous package intended for short, dedicated, space astronomy missions, but can be used for other types of experiments. It is deployed from the Shuttle and then retrieved after approximately 100 hours in space.

EURECA, managed by the European Space Agency (ESA), will be launched by the Shuttle and is intended to perform a number of experiments within defined volume, power, and telemetry capabilities. The first EURECA is manifested for deployment in 1990, with retrieval and return to Earth about 6 months later. The experiments for this EURECA have already been selected, but a second EURECA is expected to fly 18 months later, and there are plans to support exobiology experiments with this flight.

There are thus a wide variety of opportunities in Earth orbit that exobiologists can potentially exploit during the next 15 years using either expendable launch vehicles or the Space Shuttle. The vehicle chosen to carry out any investigation will depend on the services required, the science objectives, and the anticipated funds available.

In addition to the orbital spacecraft providing permanent or retrievable platforms for exobiology experimentation, a number of telescopes are expected to be launched in the next two decades. Some of these will be free-flyers, and some will be attached to the Space Station or one of its platforms. They will have lifetimes ranging from a few years to decades—depending on the plans for on-orbit servicing. These telescopes will provide facilities for the exobiology community to study the origin and evolution of the biogenic elements and compounds remotely.

Appendix B presents a compilation of the currently envisioned instrumental capabilities of the various orbital telescopes. The spectral coverage and approximate launch dates are summarized in figure 2-1. It is not yet clear how the Challenger accident or the construction of the Space Station will affect these specific dates, and they should probably be interpreted as giving only the most likely order of launch. Appendix C provides a definition of frequency and wavelength equivalents and Appendix D gives the apparent angular scales of various objects at specified distances; these will be useful for interpreting figure 2-1 and subsequent tables. Table 2-1 enumerates the telescopes being planned by NASA; Table 2-2 lists the ESA telescope projects that have been given approval or strong support in the long-term planning process and which have invited U.S. participation. For every telescope these tables contain, a definition of the mission name or acronym, a tentative launch date, and a description of the current status of the instrumentation is included. Table 2-1 also lists the NASA Center or Research Unit with primary responsibility for the telescope instrumentation. Appendix B provides more detail and describes each of the proposed observing instruments in terms of its frequency or wavelength coverage, the size of the instantaneous field of view that can be imaged, the best spatial resolution that can be achieved, the spectral resolving power, and the limiting sensitivity that can be obtained with modest integration time. Where applicable, the maximum sampling rate and polarization characteristics are also provided. In many instances the data are incomplete because instrument packages have not yet been chosen or outlined.

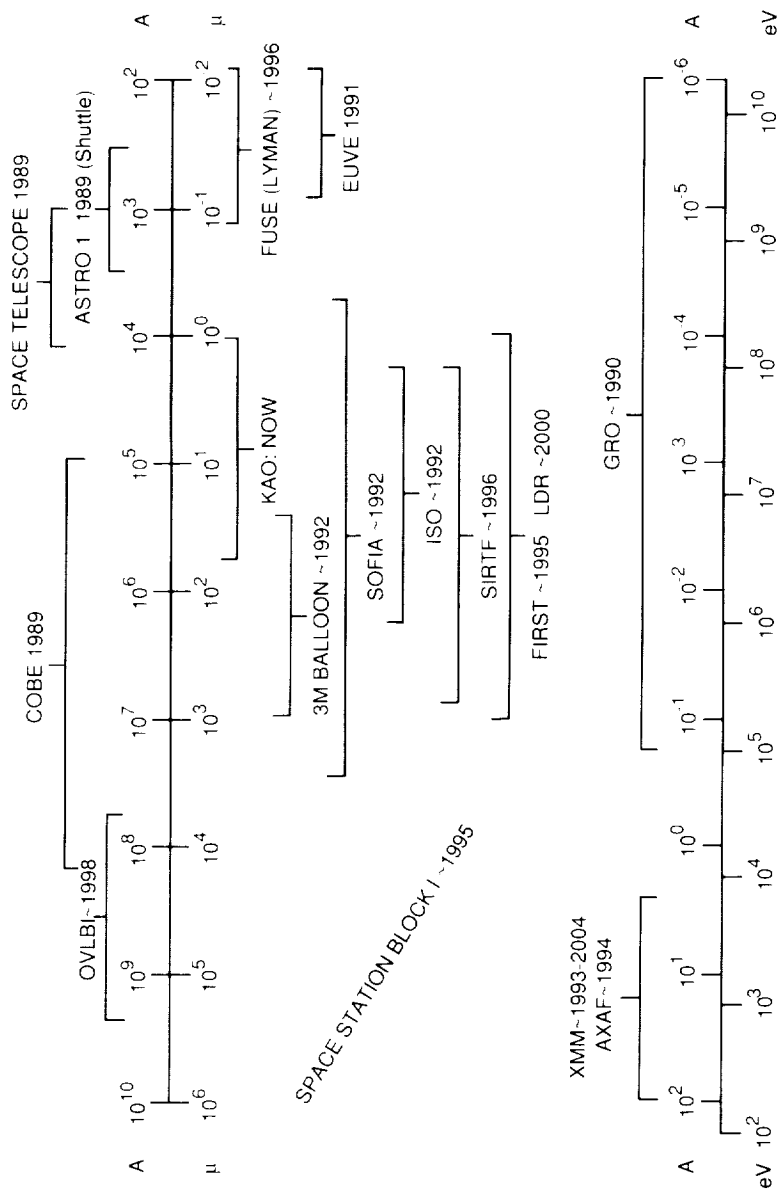


Figure 2-1. The approximate spectral coverage and launch dates for the currently envisioned Earth-orbiting observatories.

TABLE 2-1

NASA Telescopes

ORBITAL

IUE	International Ultraviolet Explorer (1977) [Goddard Space Flight Center]. This spacecraft has outlived its original planned lifetime, but it continues to function and is supported by an active guest investigator program. Longevity is unpredictable, no plans exist to decommission the spacecraft.
HST	Hubble Space Telescope (1989) [Space Telescope Science Institute]. The first generation of instruments is constructed and integrated into the telescope, awaiting launch. These instruments are detailed in Appendix B. The next generation of instruments (to be installed on orbit ~1994) have been selected for competitive development during 1986-88. All three selected instruments are described in Appendix B.
ASTRO	Hopkins Ultraviolet Telescope (HUT) [Johns Hopkins University], Ultraviolet Imaging Telescope (UIT) [Goddard Space Flight Center], Wisconsin Ultraviolet Photopolarimetry Experiment (WUPPE) [University of Wisconsin]. These instruments have been finalized by their respective proposers and will be flown at least twice as a package Shuttle payload. Collaboration with the principal investigators as a guest investigator is possible and will be solicited by an announcement of opportunity (AO) for flights in 1989.
COBE	Cosmic Background Explorer (1989) [Goddard Space Flight Center]. The instrument complement is finalized and is detailed in Appendix B.
EUVE	Extreme Ultraviolet Explorer (1991) [University of California Berkeley Space Sciences Laboratory]. The instrument complement is finalized and is detailed in Appendix B.
GRO	Gamma Ray Observatory (1990) [Marshall Space Flight Center]. The instrument complement is finalized and is detailed in Appendix B.
AXAF	Advanced X-ray Astrophysics Facility (1994) [Goddard Space Flight Center]. The instrument complement has been selected on the basis of a competitive AO, but implementation is not yet

complete and some modification may still be possible. The selected instrumentation is detailed in Appendix B.

- FUSE Lyman Far Ultraviolet Spectroscopy Explorer (LYMAN) (1995). Potential Explorer-class mission if collaboration can be secured to provide cost-sharing. A strawman instrument complement has been defined for planning purposes, no AO has yet been issued. The strawman instrument complement is listed in Appendix B.

- Block I Initial Configuration for the Space Station (1995). Phase A studies of the Block I Space Station have been completed. The final definition of the module structures and positioning and the selection of the instrumentation associated with these modules is expected to be completed during 1988.

- SIRTF Space Infrared Telescope Facility (1996) [Ames Research Center]. The instrument complement has been selected on the basis of a competitive AO, but implementation is not yet complete and some modification may still be possible. The selected instrumentation is detailed in Appendix B.

- LDR Large Deployable Reflector (2000) [Jet Propulsion Laboratory and Ames Research Center]. In preproject phase, waiting phase A study monies. Strawman instrument complement detailed in Appendix B.

- OVLBI Orbiting Very Long Baseline Interferometry (1998) [Jet Propulsion Laboratory]. Possible Explorer-class mission. In preproject phase, awaiting phase A study monies. Strawman instrument complement detailed in Appendix B.

AIRBORNE

- KAO Kuiper Airborne Observatory (now) [Ames Research Center]. Telescope is a permanent fixture; new backends are supplied by each observer.

- 3M Balloon Balloon-Borne Three-Meter Telescope for Far-Infrared and Submillimeter Astronomy (1989) [Smithsonian Institution Astrophysical Observatory, University of Arizona, and University of Chicago]. One of three balloon programs under consideration. The instrument complement is finalized and is detailed in Appendix B.

SOFIA	Stratospheric Observatory for Infrared Astronomy (1992) [Ames Research Center]. A 3.5-m telescope proposed to be flown on a 747SP aircraft as a replacement for the very successful KAO during the interval prior to SIRTf. Backend instrumentation supplied by observers. Some performance specifications are given in Appendix B.
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TABLE 2-2

ESA Telescopes with Potential for U.S. Collaboration

ORBITAL

ISO	Infrared Space Observatory (1992). Approved mission. The instrument complement has been selected on the basis of a competitive AO, but implementation is not yet complete and some modification may still be possible. The selected instrumentation is detailed in Appendix B.
FIRST	Far Infrared Space Telescope (1995). One of the four cornerstones of ESA's long-term plans for space missions. Mission not yet approved and the telescope may turn into an interferometer. Strawman instrument complement described in Appendix B.
XMM	X-ray Multiple Mission (1993-2004). A series of missions that form one of the cornerstones of ESA's long-term plans for space missions. Intended to complement NASA's AXAF (which excels at spatial resolution) by providing excellent spectral resolution from soft to hard X-ray regime. No missions yet approved.
COLUMBUS	Space-Station-related modules. This label covers ESA efforts to define which of their spacecraft and on-orbit experiments could benefit from a human-tended station.

2.2 Space Station

The Space Station is now envisioned as an evolving facility, with the first phase, called Block I, scheduled to be functioning during the mid- to late-1990s. The exact configuration of the station and the experiments that will be included in Block I have yet to be determined. The station configuration and its evolution from Block I to Block II appear to be well defined, but decisions on science issues have not been made; the summary that follows will require updating.

The Space Station is not just one structure, but is composed of four basic components: the manned core, free flyers tended by the station, co-orbiting platforms, and polar orbiting platforms. The core is by far the largest and most complex element. It must provide the main structure to which the Shuttle will dock and in which the astronauts will live. It will be constructed in a low Earth orbit at an estimated altitude of 500 km with an orbital inclination of 28.5° to the equator. Block I will consist of a 135-m horizontal boom with photovoltaic arrays at each end to produce 50 kW of power. A single polar orbiting platform for Earth remote sensing will also be part of the Block I configuration. At the center of mass will be two interconnected pressurized modules. One of these modules will be for the six crew members, providing living quarters, storage areas, and communications, and one will be a laboratory. It is anticipated that the modules will later be joined by two additional laboratory modules, one from Japan and one from Germany. Block II will add two horizontal towers with an upper cross boom for mounting attached payloads and telescopes and a lower boom for Earth-looking instruments. The power will be increased to 75 kW. Solar dynamic arrays and a satellite servicing facility for free flyers and co-orbiting platforms will be added.

The free-flying or attached platforms provide a shared environment for instrumentation modules, which can be periodically serviced and changed out. The co-orbiting free-flying platforms will be tended by the station crew, but the polar orbit platforms will be serviced by the Shuttle. The free flyers provide their own power, and have generally been derived from the scientific satellites and telescopes that have been planned in advance of the Space Station concept. In addition, platforms can be attached to the Space Station boom, providing greater ease in servicing and experiment retrieval, though in a more contaminated environment. These platforms generally provide their own power, but experiment control and telemetry is possible through sharing of Space Station facilities. The Space Station offers the possibility that the platforms can be tended or retrieved by the crew using an orbital maneuvering vehicle (OMV) that is being developed in parallel with the Space Station, but will not be functional at Block I. Another parallel development is the orbital transfer vehicle (OTV), required to place free flyers or platforms in higher orbits, up to geosynchronous orbit.

The scientific community has been quick to review the potential offered by the Space Station. With the caveat that sufficient funds be provided to continue the orderly development of the well-planned, long-term space missions, some of which are already under way, they have endorsed the use of the Space Station for many of the other missions and have conceived of new experiments that take specific advantage of the Station environment. Competition for space in Block I laboratory modules or on platforms is severe. The following list presents the facilities of interest to the exobiology community. These items have high priority, and should remain in the final version of Block I for 1993 to 1996.

Tentative Space Station Complement at Block I

CORE

- Astrometric Telescope Facility
- Life Sciences Research Facility
- Microgravity and Materials-Processing Facility
- Cosmic Dust Collector

FREE FLYERS

- HST
- GRO
- AXAF

CO-ORBITING PLATFORMS (NUMBER OF PAYLOADS UNDER REVIEW)

SIRTF

POLAR PLATFORM(S)

2.3 Lunar Base

A lunar base is a natural extension of NASA's Space Station program, technically and programatically, and could be in its initial stages of implacment in the first decade of the 21st century. Technically, the lunar base can utilize or build directly upon many of the systems developed for Space Station. Programatically, the construction of a lunar base fits logically after the development of Space Station and OTV technology.

The rationale for developing a lunar base is to advance scientific understanding, to learn to utilize lunar material and the lunar environment beneficially in the development of the space infrastructure, and to develop the capability for extended, even permanent, habitation in space. Investigations into the origin and history of the Moon can uniquely be carried out at a lunar base and these may help us to better understand the early history of the Earth and the prevailing conditions that lead to the origin of life. Long-baseline radio interferometers and very large optical arrays can improve upon currently planned orbital observatories in both sensitivity and spatial resolution. These are crucial to the study of the origin and evolution of the biogenic elements and compounds; particularly, attempts to image and spectroscopically examine the atmosphere of a distant planet, or to study the formation of a nearby planetary system and understand the processes by which complex interstellar organic compounds might survive their inclusion into the protoplanetary nebula. New investigations into the properties of matter may be possible utilizing the high vacuum and extremes of temperature that may be easily maintained on the Moon for very long times.

Among the exobiological studies that can be carried out uniquely at a lunar base are the direct search for evidence of life forms in interplanetary space (panspermia); determination of the quantity and form of organic and biogenic compounds in lunar soil (in a very-low-organic-background laboratory environment); study of the survivability of terrestrial organisms in the lunar environment; study of the frequency history of cometary impacts on the Moon (and, consequently, Earth); gathering of evidence pertinent to the theory of episodic extinctions on Earth related to cosmic events; and conduct of astronomical investigations of interest to the exobiology community such as those previously mentioned. Also, the search for extraterrestrial intelligence (SETI) may require the radio-quiet lunar far side in order to conduct a sufficiently sensitive search, shielded from terrestrial interference.

According to current concepts, the initial lunar base will have aspects of the Earth-orbit Space Station from which it will evolve. The early base will have geological and biological laboratory facilities focusing on understanding how to best utilize the lunar materials and environment for scientific investigations and life-support functions. As production capability grows at the lunar base, new facilities may become available for research. This includes very large, very high vacuum chambers; very high temperature and very low temperature systems of substantial dimensions; chambers of very low natural magnetic field; very low natural radiation background facilities (buried facilities, with natural-material barriers constructed from uranium-potassium-free lunar materials); facilities nearly totally free of light (organic) elements and free or capable of being isolated from human-introduced biogenic compounds; and laboratories free of metallic contaminants found in many terrestrial environments. All of these should be rather easily developed on the Moon and can be made available inexpensively once the initial base is able to govern its own growth.

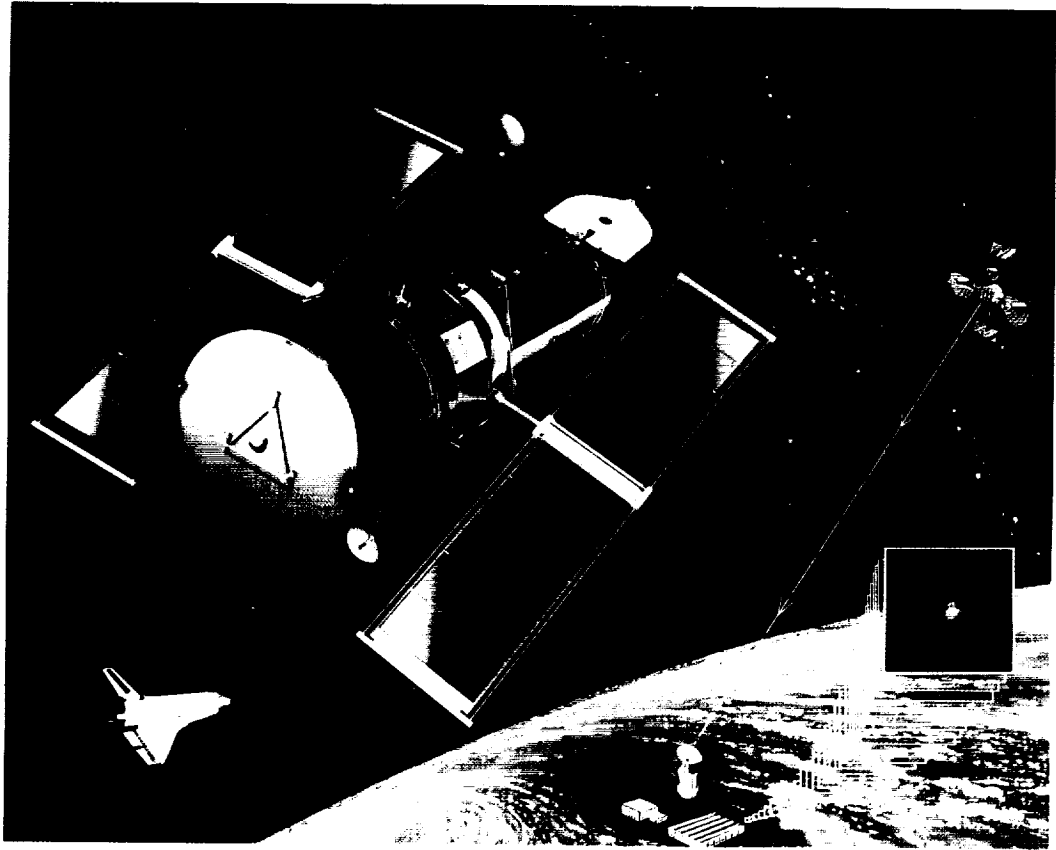
Suggestions for Further Reading

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Chapter III

Observational Exobiology

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Since life (as we know it) depends upon its environment for development and survival, the origin and evolution of life are integral parts of the physical and chemical processes that govern the formation and evolution of the planets. The formation and evolution of a planet is intimately bound to the evolution of its sun, a star. Stars themselves are the manufacturing plants for all of the biogenic elements; their birth and death cycle is governed by the laws of physics in this universe. Thus it should be no surprise that in attempting to understand the origin and evolution of the biogenic elements and compounds, the exobiology community has, over the past decade, developed an increasing interest in the results of astronomical observations. Much of what is known or conjectured about the processes that led to the abiotic chemical evolution of organic matter in the vicinity of the planet Earth was derived from the observations conducted by astronomers and astrophysicists. The observational results have been combined with knowledge gained from the collection and analyses of pristine materials of terrestrial and extraterrestrial origin, and have been supported by laboratory attempts at chemical synthesis and theoretical models of complex chemistries in various environments. There now appears to be a marginally self-consistent outline of the pathways leading from the stellar nucleosynthesis of carbon, oxygen, nitrogen, phosphorus, sulfur, and other biologically significant trace elements to their inclusion into planetesimal sized bodies within the young protosolar nebula. While this outline is self-consistent, it is far from complete, and many of the most interesting details remain to be supplied by more observational, experimental, and theoretical effort.

Hubble Space Telescope

3.1 Cosmic History of the Biogenic Elements and Compounds

The principal matter of the early universe was hydrogen and helium (fig. 3-1). Local density concentrations in the overall expansion of the young universe led to the gravitational contraction of galactic-mass gas clouds within which further fragmentation and further collapse led to the formation of the first generation of Milky Way stars. Or, perhaps the stars began to collapse first and aggregations of these protostellar clouds eventually formed galactic-mass assemblages of gas and stars. Either way, in those collapsing stellar-mass fragments where the central temperature rose to $\sim 10^7$ K, hydrogen atoms fused to form helium and produced a stable, self-luminous, main-sequence star. When the hydrogen fuel was exhausted, further contraction of the stellar core raised the temperature to $\sim 10^8$ K, whereupon helium could fuse to form carbon. Eventual depletion of helium resulted in further core contraction and an increased temperature until oxygen could be fused from carbon, and so on and so on, until the peak of the nuclear binding energy curve was encountered at ^{56}Fe .

Further fusion reactions being endothermic, the fate of the now-evolved, old giant star depends on its initial mass and how much of its outer layers it shed with each phase of core burning and gravitational readjustment. Sufficiently small stars enter a stable, nonnuclear-burning, white dwarf configuration in which the pressure from a degenerate gas provides the needed support against further gravitational collapse. Gradually the central temperature drops as the white dwarf cools off, evolving into an increasingly unobservable black dwarf; it eventually "goes out." From the point of view of the biogenic elements, except for the mass that has been lost from the stellar surface along the way, such stars represent a graveyard in which the elements are entombed and are never again accessible for chemical evolution. However, if the star runs out of nuclear fuel and is still sufficiently massive, no stable white dwarf configuration is accessible. These massive stars end their life cycle not with a whimper, like the white dwarfs, but with a bang. In a spectacular supernova explosion, much of the outer mass of the star is hurled back into the interstellar medium while the stellar core implodes to another stable configuration: a neutron star or a black hole. During this violent stellar demise, enough energy is available to drive the endothermic fusion reactions, thereby producing the full repertoire of stable elements as well as many unstable isotopes. Thus, the first generation of stars seeded the interstellar medium with heavy elements that became incorporated into subsequent generations of stars. These then have the potential for somewhat more complex nuclear reactions, particularly in the conversion of hydrogen to helium. Like their predecessors, some of these later stars return enriched matter to the interstellar medium and lock the rest of it away into stable, degenerate configurations. Currently, something like a few solar masses of enriched material are added to the Milky Way's interstellar medium each year, and the mean metallicity (i.e., the abundance of chemical elements heavier than helium) of the galaxy does not appear to have changed much since the collapse of the protosun.

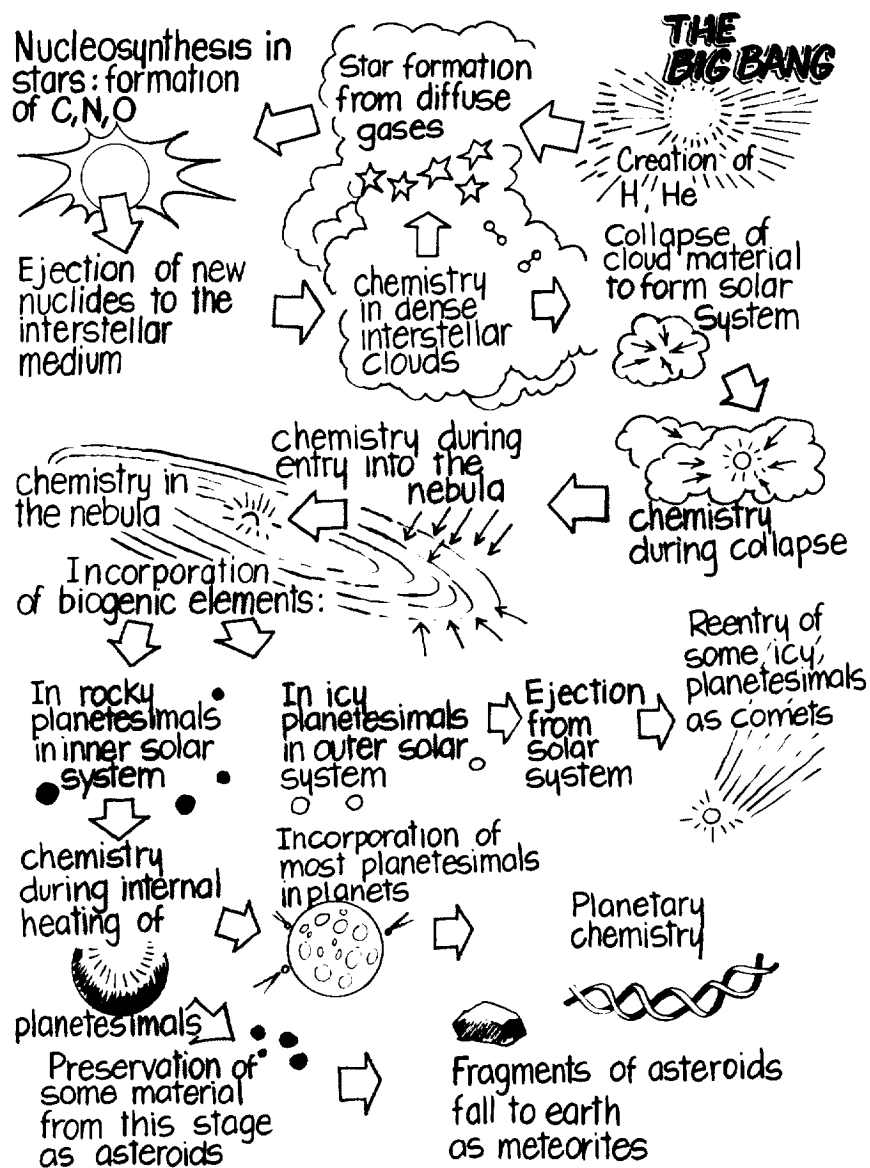


Figure 3-1. The cosmic history of the biogenic elements and compounds—from the Big Bang to the formation of planets.

On average, it takes about five billion years for the biogenic elements produced within one star to become gravitationally bound within a later-generation star. Along the way from one stellar interior to the next, the biogenic elements cycle in and out of several types of environments within the interstellar medium. Here they undergo chemical and isotopic alterations and suffer a large number of near misses in the star-formation game. One important type of interstellar environment is the giant molecular cloud. These are observed to be active nurseries for stars being born at this time. Each such cloud may have a mass of up to $10^6 M_{\odot}$, densities ranging from 10^4 to 10^6 cm^{-3} , and cool temperatures, ~ 10 to 50 K . By the time it is finally dispersed (in part by the energetics of star formation), such a cloud will have converted only about $100 M_{\odot}$ into stars. During their lifetimes the giant molecular clouds serve as very effective molecule and dust factories powered by radiation fields, hydrodynamical energies of the embedded newly forming stars, and interstellar cosmic ray flux. More than 70 organic molecules have been detected in interstellar space, mostly within giant molecular clouds, and the unidentified spectral lines resulting from radio observations indicate that the list is incomplete.

Within the giant molecular cloud complexes it is clear that H_2 is formed on the surface of dust grains, but the composition and origin of the dust are much debated. Dust is formed when the enriched elemental gas in the outer layers of an evolving star is blown off in a stellar wind. Subsequent cooling of the wind leads to condensation of grains far from the stellar surface. Grains are also formed in the winds that blow off newly formed stars; in the novae outbursts of dying stars; perhaps in the rapidly cooling regions behind shock waves propagating throughout the molecular clouds; and perhaps, too, in the cooling ejecta of supernovae, whose strong shock waves also destroy preexisting dust grains throughout a large volume of the interstellar medium. This dust may be composed of carbon and other biogenic elements if it condensed in the wind from a giant carbon star, or it may perhaps provide a catalytic surface for the transformation of the biogenic elements and compounds into ever more complex organic molecules within the molecular clouds. The dust in molecular clouds is important as a shield against ultraviolet radiation without doubt, but its composition and the exact role it plays in the cloud chemistry beyond the formation of H_2 is still questioned. Even in the event that the dust plays no active role in the gas-phase chemistry, it may still be of particular importance to exobiology if it provided a vehicle for inclusion of the biogenic elements into the protosolar nebula in a highly processed form. There is a growing body of evidence, based on isotopic anomalies, that some interstellar dust has survived its introduction into the nebula. Whether manufactured on the surface of the grains or not, some organic molecules do coat solid grains of dust and reveal themselves by the vibrational spectra observed in the infrared.

Not all of the gas and dust bound in the initial fragment that collapsed to form the Sun was incorporated into the central star, and some that was may subsequently have been liberated via a strong T Tauri wind during the Sun's infancy. A certain unknown fraction of the collapsing cloud must have been incorporated into a toroidal nebulosity orbiting the developing stellar core. This solar nebula provided the material from which the solar system planets were formed as well as an environment for chemical processing of interstellar biogenic elements and compounds into both more and less complex forms. The solar nebula flattened into a viscous accretion disk, bounded above and below by shocks. Late-arriving interstellar materials experienced more or less traumatic chemical processing, depending on the location at which they crossed these shock fronts and the initial velocity of the particles falling onto the shocks. The picture is particularly unclear with respect to dust grains; some grains coated with organic mantles may have entered the solar nebula with their complement of biogenic elements unaltered; some grains without complex organic mantles may have grown them as a result of the chemistry induced by the added energies during the encounter; or some (perhaps all) grains may have been sputtered away and converted into their basic elemental components during the shock wave passage, only to condense anew within the early nebula itself. That grains were present within the early nebula seems undeniable. Dust is observed associated with comets which presumably preserve the primitive nebular material; whether the grains are of nebular or presolar origin is unknown. Processing of and on the grains did not cease with their inclusion in the solar nebula. Turbulence may have cycled the nebular material between extremely diverse thermal locales on a time scale that would have resulted in transformed, possibly enhanced, chemical complexity. Aggregation would have caused material to settle into the mid-plane of the accretion disk, and fragmentation of this plane would have led to the incorporation of grains and macromolecules into kilometer or larger size planetesimals where internal heating and collisions may have strongly metamorphosed the included biogenic elements and compounds. Aggregates of this size would have been resistant to the subsequent dispersal of the solar nebula, and would eventually have formed into the planets, satellites, asteroids, and comets. Some of the nebular material, initially dispersed, might have condensed and reentered the solar system as icy comets at a later date.

Chemical processing in the early solar system, evidenced by certain elemental fractionation patterns in primitive meteorites, could also potentially cause small isotopic fractionations for some of the elements in those meteorites. Isotopic variations are, in fact, observed in such meteorites, but in a significant number of cases the nature and/or magnitude of those variations are incompatible with a local, i.e., solar system, process and are therefore attributed to presolar processing. That processing can be either nucleosynthetic or chemical. An example of

the former is supplied by certain carbon-bearing compounds found in carbonaceous meteorites, characterized by a $^{12}\text{C}/^{13}\text{C}$ ratio of 42, compared with the canonical solar system value of 89. An origin by formation in the atmosphere of a red giant star is inferred for such grains. An example of evidence for presolar chemical processing is the deuterium content of meteoritic organic matter, with D/H values over 20 times the galactic value. This is commonly attributed to ion-molecule reactions at the low temperatures of interstellar clouds. The presence of such material in meteorites is evidence that some presolar organic matter was able to survive entry into the solar nebula.

Suggestions for Further Reading

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3.2 Remote Observations

Most of our information concerning extraterrestrial objects and environments comes from the analysis of electromagnetic radiation. The intensity and polarization of the radiation, at a particular frequency, in a certain direction, and at a specific time, can be measured to provide information of particular interest to exobiology, for example:

1. The existence of extra-solar planets that might serve as suitable hosts for the chemical evolution of life
2. The abundances and distribution of biogenic substances throughout the cosmos
3. The conditions under which complex organic molecules form or are destroyed
4. The conditions under which solids composed of the biogenic elements form from gases
5. The processes in circumstellar, interstellar, and nebular stages of physical-chemical evolution which govern the composition and distribution of biogenic matter during its transit from stage to stage

Exobiologists need access to observing platforms in space. Observing from spacecraft has clear advantages over ground-based viewing because of the opacity of the atmosphere in many regions of the electromagnetic spectrum (fig. 3-2): the gamma-ray, X-ray, ultraviolet, parts of the infrared, most of the submillimeter, and parts of the millimeter. Even in those spectral regions where the atmosphere is generally transparent, there are specific frequencies where absorption or emission by species in the air precludes ground-based observations.

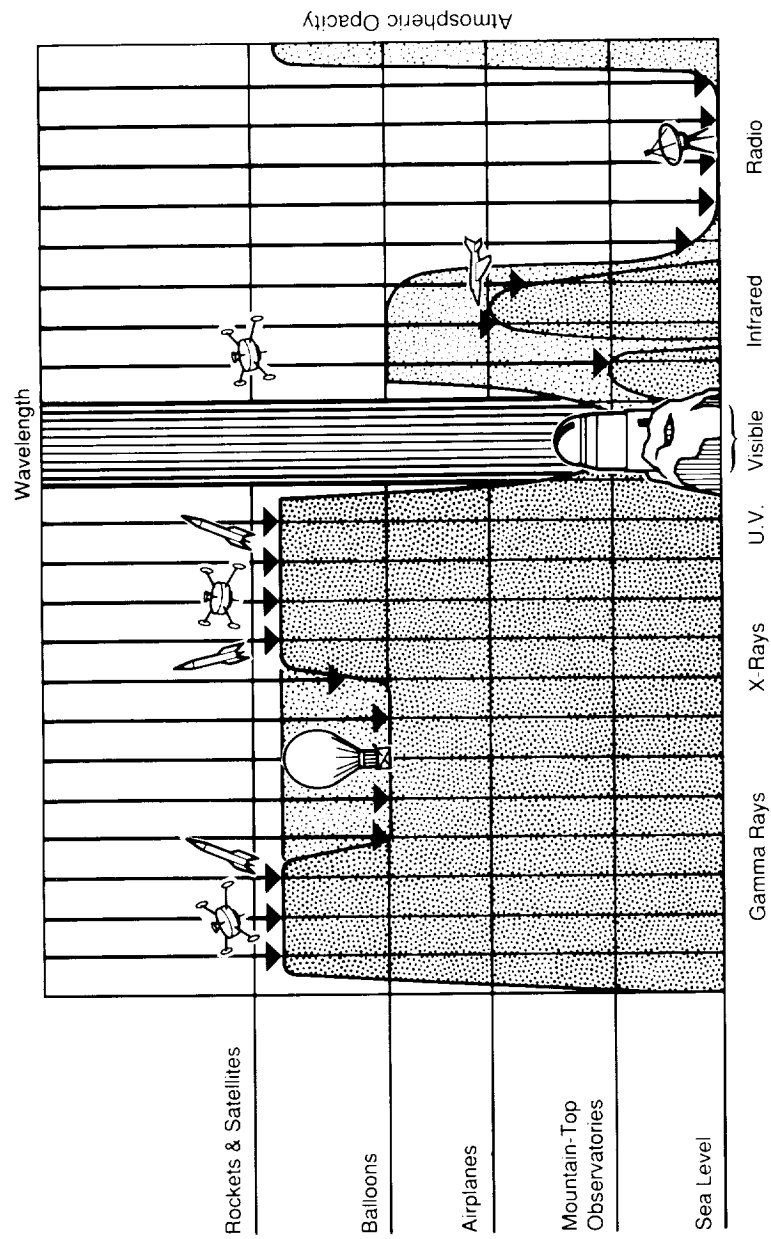


Figure 3-2. Observatories in space, high above the Earth's absorbing atmosphere, provide new vistas on the universe.

Further benefits accrue due to the possibility for improved spatial resolution (fig. 3-3). The resolution of a telescope in orbit is limited by the quality of its optics rather than by the stability of the atmosphere. Also, in the near-weightless environment of low Earth orbit, larger collecting areas are possible, providing higher spatial resolution and greater sensitivity. Spatial resolution can also be improved by constructing interferometers with much longer baselines than are possible on the ground. Sensitivity at wavelengths for which thermal emission is important can be improved in Earth orbit relative to the ground by utilizing cryogenically cooled telescopes and receivers. The decreased levels of such human-caused "noise" as light pollution and radio frequency interference (RFI) also can lead to improved sensitivity in orbit. Note that many of the improvements gained by placing a telescope in low Earth orbit are magnified by going to a lunar base, particularly if it is located on the Moon's far side.

Although gamma-ray measurements are useful for tracing the broad distribution of interstellar matter and cosmic rays in the galactic plane, and although X-ray measurements are useful for studying the very active phases in the development of recently formed stars, they preferentially sample the hottest and most energetic environments, as revealed by electronic transitions within atomic species. Since these wavelengths cannot directly investigate the biogenic elements in their more complex molecular configurations, their utility for exobiology is less immediate than other wavelengths. Absorption line studies in the ultraviolet of regions rich in molecules and dust particles are impossible at large distances because of extinction by dust. Even with the high-resolution spectrograph on the Space Telescope, only relatively transparent regions with visual extinctions $A_V < \sim 4$ magnitudes (corresponding to foreground hydrogen column densities $< \sim 7 \times 10^{21} \text{ cm}^{-2}$) will be accessible in the ultraviolet at high resolution. Even so, these thin regions can yield valuable information about elemental abundances, depletion of elements from the gas onto solids, and the chemistry of small molecules. Of greatest value to exobiology will be the exploitation of those parts of the spectrum in the infrared, submillimeter, and millimeter regions that are inaccessible from Earth. These spectral regions typically bracket the condition where the excitation temperature of the molecular transitions can be provided by the ambient radiation field ($h\nu \cong kT_{\text{ex}}$) for many chemical species of exobiological interest for a wide variety of environments. Thus both absorption and emission can be observed, depending on the physical conditions. The infrared region from 2 to 20 μm has many diagnostic advantages for studying dilute matter. Chemically important, nonpolar molecules such as methane, acetylene, and carbon dioxide, which lack strongly allowed radio spectra, have strong vibrational transitions in this region of the spectrum. They are among the simplest molecular forms of carbon, the central element of exobiology, and thus they are missing links in our understanding of the chemical evolution of interstellar and circumstellar matter. Observation at high spectral resolution can provide the rotational structure of a vibrational band. It is thus possible to

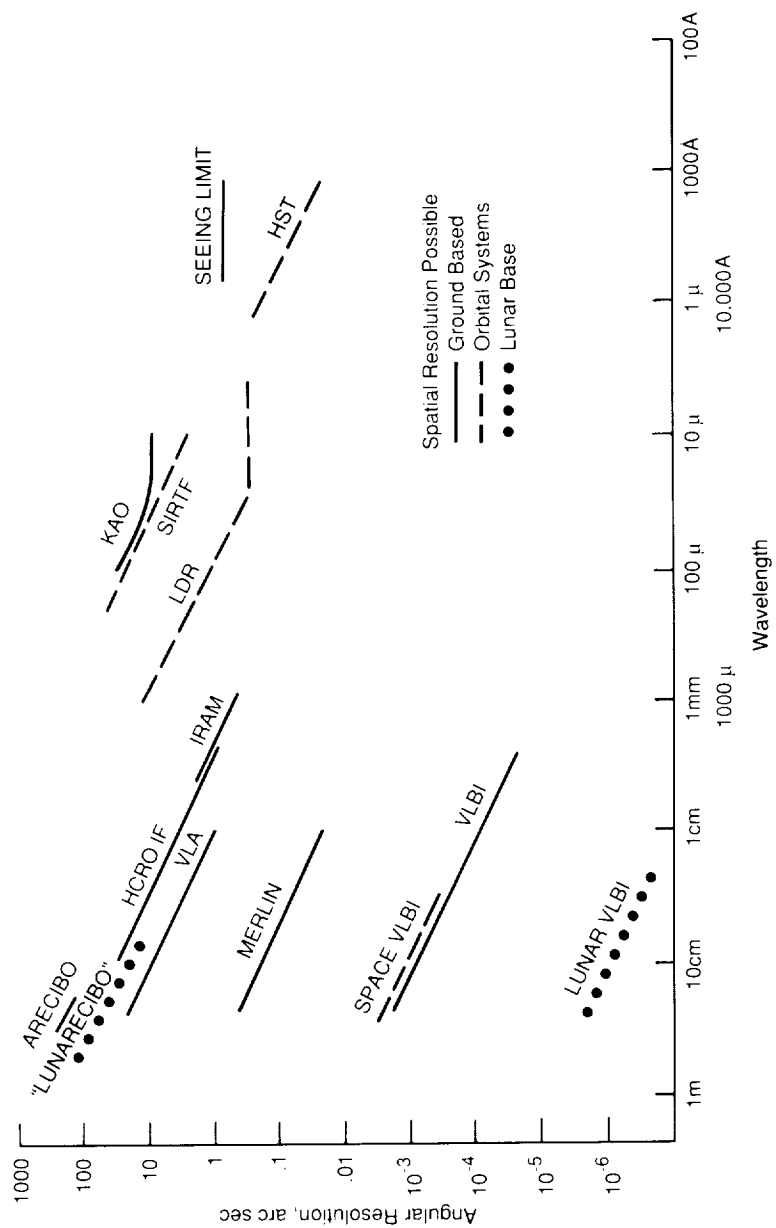


Figure 3-3. An important advantage of space telescopes is increased spatial (angular) resolution.

obtain in a single measurement complete information on energy-level population distributions and hence to infer densities, temperatures, and total abundances accurately for material that is either sufficiently warm to excite these transitions or that lies in front of a strong continuum source. Such information is more difficult to obtain from isolated measurements of individual rotational transitions in the radio regime, although this approach is necessary for the typically cold interstellar clouds. In the infrared, submillimeter, and millimeter spectral regions, it is possible from space to observe chemically important species like oxygen and water that cannot readily be studied from Earth because their spectra are obliterated by atmospheric absorption.

Spectrometers of high spectral resolution (with resolving power $\lambda/\Delta\lambda \sim 10^5$) are needed for observations of molecular lines to obtain information of diagnostic value. High spatial resolution is also desirable to investigate phenomena occurring both at distant locations within the Milky Way and in other galaxies. The study of protoplanetary systems and accretion shocks surrounding them in star-forming regions provides a particularly stringent requirement on spatial resolution: ~ 0.01 arcsec (see Appendix C). For the immediate future, this may not be available. To achieve both high spectral and high spatial resolution simultaneously requires extremely large apertures (and/or interferometers) to collect enough photons.

The orbital observatories will permit access to the far-infrared and submillimeter regions of the spectrum that have previously been mostly unexplored. The required data base of fundamental frequencies and preferred molecular configurations does not now exist to guide the conduct of observations or the interpretation of data from this wavelength regime. In order to take full advantage of orbital observation opportunities, a strong ground-based laboratory research program must be pursued. The infrared and submillimeter spectra of many biogenic compounds are extremely rich, and a very high degree of accuracy is required to allow chemical specificity. Laboratory studies at low pressures and temperatures representative of the interstellar environment can provide definite predictions of spectral characteristics. However, theoretical calculations are also required to deduce the frequencies of the most probable transitions for molecules and radicals which are too reactive or otherwise not amenable to ordinary laboratory techniques. This becomes both increasingly more difficult and more important with increasing molecular weight. Laboratory study is also needed to understand the properties of the dust grains that were cycled through many phases of the stellar and interstellar media before being incorporated into the solid bodies of the solar system. These grains may be a primary source of carbon, and in addition the molecular mantles manufactured on the grain surfaces in the molecular cloud complexes may provide a significant source of highly processed organic compounds that could find their way into other protostellar nebulae and strongly influence their future evolution toward life.

In the subsequent sections of this chapter, specific examples are presented of the kinds of data that would be most useful for exobiology. From a study of the type of instrumentation that will probably be available in orbit (described in Appendix B), the members of the Workshop have concluded that many of these data should be obtainable in the near future. Attempts have been made to identify those areas in which modification of planned instrumentation would be desirable. The individual subsections are organized so that each one discusses problems relating to a particular astrophysical environment. They are ordered with respect to distance, starting with those closest in our own solar system and progressing outward to studies of external galaxies. Chapter 6 provides a prioritized summary of the various observational projects discussed in all of these subsections.

Suggestions for Further Reading

Harwit, M.; and Neal, V.: *The Great Observatories for Space Astrophysics*. NASA Astrophysics Division, Washington, 1985.

European Space Science Horizon 2000. ESA SP-1070, 1984.

3.3 Planetary Atmospheres

What useful exobiological information can be obtained from the study of planetary atmospheres? Although little can be learned about actual local biology (should it exist) through comparative studies of the planets and their atmospheres, much can be learned about the formation and properties of environments that may be necessary for life and, by extension, about the development of our own environment. Information about environments in which life arose in the solar system and those in which it apparently did not will provide constraints on the conditions favorable for the origin of life and, by implication, the likelihood of the existence of such environments and life elsewhere. At the most general level, we want to understand the chemistry of the biogenic elements and compounds in the solar system at the present time as well as in the past. Some basic problems are summarized by the following questions:

1. From what did the planets form; what can the planets and their atmospheres tell us about the primordial, pre-solar nebula?
2. How did the planets form? Did they form by simple gravitational collapse of parts of the nebula or by accretion of grains? What does this say about the possible existence of planets suitable for life in other stellar systems?
3. What are the conditions necessary for the stable existence of the different atmospheres found in the solar system, and how did they form?
4. How have these atmospheres evolved since their initial formation? This

question encompasses sources for the observed molecules and aerosols, production of useful biological precursors, effects of various types of energy, processes that lead to the conversion of an atmosphere from oxygen-free to oxygen-containing, and any other conditions that led to the various planetary atmospheres.

5. What drives atmospheric dynamics and how may these drivers affect conditions favorable for the origin of life?

6. Are the other atmospheres found in the solar system useful as models for the atmosphere of the early Earth?

It is probable that the information we can obtain from Earth orbital observations of the planets and other solar system bodies will allow us to formulate and test models for the formation and subsequent evolution of the solar system.

Lander and orbital spacecraft studies of Mars and Venus have yielded detailed information on the composition of their atmospheres and some indications of surface composition. Further investigations concerning the possibility of fossil remains of microbial life, the search for subsurface water, and the determination of the length of time that liquid water was present on the surface of both planets are very relevant to exobiology. Detailed data are needed for these studies and will require *in situ* experiments or sample returns. Several such studies are in the conceptual and planning stages and one, Mars Observer, which will study the atmosphere and surface from local orbit, is being developed for launch. Further observations from the ground or Earth orbit will be useful in the selection of sites for *in situ* studies or collection of samples.

The outer planets, however, present an area where extremely useful remote observations could be made because less is known about their atmospheres. Moreover, in some ways they are models of the early Earth, particularly of the period when there was no free oxygen in the atmosphere. One interesting study has demonstrated that it is energetically feasible for organisms to live in a liquid ocean under the crustal ice on Europa. Even if life itself has not developed on the outer planets, or their satellites, study of their atmospheres will most certainly be useful for placing the origin of life in the context of the origin of the solar system. From an exobiological perspective, three basic areas of study are appropriate for the outer planets: origin of the atmospheres, evolution of the atmospheres, and searches for other examples of satellites possessing atmospheres. Each of these will be discussed in the following paragraphs.

There are currently two basic models, with some variations, to explain the origin of the outer planets, and they make different predictions about the nature of the planets' atmospheres. In the first model, a gravitational instability in the primordial nebula leads to the formation of giant gaseous protoplanets that collapse and later segregate out a core. The second model begins with the nucleation of grains and their subsequent aggregation to form the cores of the giant planets followed by a runaway accretion to collect the atmospheres. If the first model was operative the chemical elements should have been retained in solar

proportion and consequently the atmospheres should also be in solar proportions. The situation for the second model is not so simple because various fractionation processes can occur during nucleation, aggregation, and accretion. Thus the initial elemental composition would not have been preserved. Calculations suggest that, as compared to solar composition, the heavier elements (carbon, oxygen, nitrogen, etc.) should be enriched relative to the lighter hydrogen and helium. This model would favor the development of an atmosphere richer in the biogenic elements and more conducive to the abiotic synthesis of biogenic compounds and even, possibly, some form of life.

The data that are available for Jupiter and Saturn show factors of 2 to 3 enrichment in carbon (primarily in the form of methane, CH_4) relative to solar abundances and apparently a similar enrichment in nitrogen, although the latter is complicated. Nitrogen occurs mostly as ammonia, NH_3 , that is not uniformly distributed in the atmosphere because it freezes out and also reacts with hydrogen sulfide, H_2S , another atmospheric gas. These data support the nucleation model. However, oxygen (as water, H_2O) is depleted in the Jovian atmosphere by about a factor of 30. This could be because water condenses to the liquid or solid state at the higher elevations: water vapor exists only lower in the atmosphere where observation is difficult. Sulfur has not yet been detected, but H_2S is very photolabile (to form elemental sulfur) and readily reacts with NH_3 to form solid compounds. The abundance of phosphorus varies too much to be a useful discriminator, perhaps because of the reaction with H_2O in the lower atmosphere.

Isotopic data are of poor quality and provide conflicting evidence: Low-temperature equilibration of hydrogen and water in icy materials leads to an enrichment of deuterium of up to five times solar, but observations of hydrogen deuteride (HD) and deuterio-methane (CH_3D) suggest a nearly solar ratio. This result implies that low-temperature H/D equilibration has not contributed to the isotopic composition and therefore that aggregation, fractionation, and accretion of an atmosphere characterized the formation of Jupiter. However, data on the carbon isotopes suggest that $^{12}\text{C}/^{13}\text{C}$ is about 1.8 times solar, opposite what should be observed if fractionation processes did take place. One hypothesis is that the Jovian $^{12}\text{C}/^{13}\text{C}$ ratio is representative of that in the primordial nebula, but if this is true why is the ratio different from that in the Sun? It may be that the isotopic composition of the solid carbonaceous condensates in the outer solar system differed from that of the bulk of the carbon that prevailed as gas.

Obviously, higher-quality observations than those currently available are necessary to more accurately define these isotopic ratios on Jupiter and Saturn and to determine them on Uranus and Neptune. The relative isotopic compositions of these four planets may be required to disentangle clues to the formation processes from signatures of early solar nebula conditions. For H_2 , HD, CH_4 , CH_3D , and NH_3 , most of the observations have been made on molecular lines that occur in the visible and near-infrared regions of the spectrum. Measurements

from Earth orbit will open the far-infrared and submillimeter regions where these small molecules have detectable transitions. Very detailed spatial studies are needed to determine the distributions of the various species over the Jovian and Saturnian disks. Velocity can also serve as a useful discriminant against the influence of local chemical and meteorological effects. Adequate determination of H_2 and HD profiles around 7000 Å requires a spectral resolving power of $>10^4$. Determination of isotopic and elemental ratios can also be made from observations of NH_3 and phosphine, PH_3 , in the infrared region. High-altitude or Earth-orbiting facilities are necessary to minimize the effects of atmospheric water and carbon dioxide (see fig. 3.2). Typical resolving powers of 1000 or better are required for adequate measurements of isotope ratios, e.g., $^{15}\text{NH}_3/^{14}\text{NH}_3$, although resolving powers of 10^5 are necessary to observe individual rotation lines. If sufficient spatial resolution (<1 arcsec) can be achieved, then local effects such as atmospheric turbulence and chemistry may be studied (see Appendix C).

Questions about the evolution of atmospheres with time may be easier to answer than questions about origins. We know from the detection of molecules that are not predicted by simple thermodynamic condensation models of the primordial nebula that outer-planet atmospheres are not in chemical equilibrium. We also know from the presence of these molecules, and from the existence of unidentified colored species that cannot be formed by freezing any of the known atmospheric constituents, that active chemistry is occurring, or has occurred, in the outer solar system. We do not know the details of such chemistry or what drives it. For example, in the upper atmosphere of Jupiter, photochemistry of methane is occurring, but are there other types of chemistry going on? What are the identities and sources of the (colored) compounds observed in the lower atmosphere where direct photochemistry of methane is unlikely? Are any of these organic compounds, and is the photochemistry there in any way related to the photochemistry likely to have been driven in the early atmosphere of the Earth? Might there indeed be sufficient chemical gradients and energy sources in the Jovian atmosphere to support the simple life forms once postulated in a paper entitled "Floaters, Bobbers, and Sinkers"?

Further information on the nature and distribution of compounds in planetary atmospheres must be obtained. For this the infrared region of the spectrum is potentially the most useful, and many observations (e.g., Voyager Infrared Interferometric Spectrometer (IRIS)) have been made. However, increased spectral and spatial resolution are required to determine how various chemical species are distributed in the atmosphere and to sort out the region from 10 to 15 μm where many molecules have absorptions. Study of the nature and distribution of compounds in the atmosphere will also yield information about the effects of various energy sources (solar ultraviolet, energetic particles, lightning) at different levels within the atmosphere and hence their relative importance to atmospheric chemistry and evolution.

Remote observations can also help determine the physical properties of atmospheres, in addition to the chemical properties. Information regarding temperature and pressure profiles and atmospheric dynamics can be obtained by measurements in the infrared and near-infrared regions and to some extent in the visible region. Both high spectral resolution and signal sensitivity are important, as they are necessary for accurate determination of line profiles and continuum absorption. Information in the far-infrared region of the spectrum will help extend temperature profiles to regions deeper in the atmospheres than is currently possible. Observations over long periods of time will help clarify effects of atmospheric dynamics on chemical abundances and, by inference, on local production of chemical species.

Another problem that may be clarified by observations from Earth-orbiting facilities is the difference between the atmospheres of Uranus and Neptune and those of Jupiter and Saturn. If all of these planets were formed by the same processes from a nebula of homogeneous composition, then the atmospheres should be similar, except for the effects of decreasing temperature with distance from the Sun. Present data suggest that although the two pairs of atmospheres are qualitatively similar, the elemental ratios (C/H, N/H, etc.) are quite different, implying different sources or formation pathways. Because of their much greater distance from us and the Sun, Uranus and Neptune appear much smaller in the sky and are dimmer than Jupiter and Saturn. Useful data are much more difficult to obtain and instruments with greater sensitivity and less atmospheric interference are needed for studies of Uranus and Neptune.

One last field of study is the search for and characterization of tenuous atmospheres in the outer solar system. Both Pluto and Triton (Neptune's satellite) have atmospheres, but very little is known about them. More information about such atmospheres would assist in understanding the overall distribution of the biogenic elements within the solar system and the associated occurrences of planetary atmospheres and hence their likelihood around planets elsewhere in the universe. Observations using instruments with extremely high sensitivity are necessary for these studies.

The study of planetary atmospheres can best be accomplished by *in situ* measurements from remote probes such as Galileo or Cassini. However, the number of such missions planned for the next two decades is extremely limited and the information obtainable relates only to a specific location and time, so that these observations must be complemented and extended by global and synoptic observations from Earth or Earth-orbit. Of the orbital spacecraft listed in Appendix B, those that will be most useful in making planetary observations are those capable of detecting the ultraviolet, infrared, and submillimeter regions of the spectrum. HST, ASTRO, IUE, FUSE, SOFIA, SIRTf, ISO, FIRST, and LDR satisfy these requirements. For continuing efforts to determine the identities, abundances, and distributions of molecular species, the greatest information to date has come from the 5- μ m window and the 10- to 15- μ m region in the infrared. From the

point of view of sensitivity, SIRTf would be the facility of choice, providing the capability to observe weak lines (e.g., those of $^{15}\text{NH}_3$ and H_2S). However, the spectral and spatial resolution as presently defined may not be adequate to make the required measurements. ISO will have a similar capability. For the stronger lines, and especially at wavelengths longer than $10\text{ }\mu\text{m}$, SOFIA could provide superior spatial and spectral resolution, and in the very near future. For faint sources and high resolution, we will have to wait for LDR. For Jupiter at least, Galileo may obtain the desired information first.

Measurements of isotope ratios require very high spectral resolution (resolving power, $\lambda/\Delta\lambda > 10^4$), and, if local variations of the ratio are to be determined, high spatial resolution as well (see Appendix C). For H_2 , HD, CH_4 , CH_3D , and NH_3 , these observations have used the visible and near-infrared regions of the spectrum, but determinations of $^{13}\text{C}/^{12}\text{C}$ and $^{15}\text{N}/^{14}\text{N}$ for Jupiter were made using bands in the infrared. If resolving powers around 10^5 can be achieved with sufficient sensitivity, then the instruments aboard HST, SOFIA, SIRTf, and LDR should be able to make useful observations. Resolving power $\lambda/\Delta\lambda > 10^3$ is not planned for the faint-object spectrograph (FOS) on HST. IUE and then FUSE will be of use if bands of HD (and of C_2H_2 , etc.) below $3000\text{ }\text{\AA}$ can be detected. For work requiring high spatial resolution (e.g., 0.8 arcsec —about one-tenth the size of the great red spot of Jupiter) we will have to wait for LDR.

Physical properties of planetary atmospheres can also be determined if accurate line shapes can be obtained. High spectral resolution and detector sensitivity are necessary to adequately characterize line profiles and to determine continuum absorption. High spatial resolution is necessary for the study of local conditions. For this work, observations must be made in the infrared or far-infrared regions. Combined data acquired with SOFIA, the SIRTf wide-field camera (WFC) or the LDR medium-resolving-power spectrometer (MRPS) should be useful to meet the proposed resolution and sensitivity requirements at different wavelengths.

The study of tenuous atmospheres surrounding Pluto and moons in the outer solar system essentially requires high detector sensitivity while maintaining sufficient spectral resolution ($\lambda/\Delta\lambda > 10^2$) to detect molecular absorption or emissions. Spatial resolution is not of great importance provided that individual objects can be isolated. For these studies the HST faint-object spectrograph (FOS) and the LDR MRPS should be useful.

Since the observations of planetary atmospheres described here primarily involve obtaining and interpreting spectra, laboratory spectra of individual molecules under proper conditions are necessary for comparison. Not only is information about line positions and strengths needed for the determination of the identities and abundances of atmospheric constituents, but the effects of pressure and temperature on spectral line shapes (and positions) need to be measured to determine the atmospheric conditions, hence the locations, where

molecular absorptions and emissions originate. A strong laboratory effort must therefore be carried out in conjunction with the observational program.

Suggestions for Further Reading

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Trafton, L.: The Atmospheres of the Outer Planets and Satellites. *Reviews of Geophysics and Space Physics*, vol. 19, 1981, p. 43.

3.4 Titan

Some of the most interesting discoveries of the Voyager mission concern Saturn's planet-sized moon, Titan. Titan, like the Earth, has an atmosphere dominated by nitrogen with a surface pressure comparable to the terrestrial value; its surface is strongly suspected to be (at least partly) liquid, possibly composed of a mixture of methane and ethane. A number of organic molecules have been identified on Titan: hydrogen cyanide (HCN), cyanoacetylene (HC_3N), and cyanogen (CN)₂. These are postulated to be products of methane (CH_4) and nitrogen (N_2) photodissociation reactions. Thus, Titan may serve as a Miller-Urey-type model of a highly reduced early Earth atmosphere in which the first stages of organic chemical evolution could take place in the atmosphere. Indeed, laboratory simulations show that a Titan-like atmosphere, primarily a N_2/CH_4 mixture, under various energetic excitations forms not only HCN, (CN)₂, and HC_3N (observed on Titan), but also CH_3CN , (HCN)₄, and finally, adenine (HCN)₅, a component of DNA. Titan thus appears as an object of exceptional interest for exobiology.

It is likely that Titan will be extensively explored by a space mission at the end of the century: a joint ESA-NASA project, Cassini, is now under study. Before this exploration, many observations need to be performed from Earth orbit. Observing Titan is difficult since it is small and faint. Sensitive Earth-orbit observations of Titan in the ultraviolet, visible, and infrared spectral ranges could significantly improve our knowledge in the 10 to 15 forthcoming years and provide valuable data complementing that which Cassini may provide.

The ultraviolet and visible spectral ranges are suitable for studying Titan's photochemistry. Two types of observations can be identified.

The first is imaging Titan in the ultraviolet and visible regions. This imaging can be accomplished in various bandpasses to within 0.1-arcsec resolution using the Space Telescope wide-field/planetary camera (WF/PC) or the faint-object camera (FOC). This camera would give about eight resolution elements across

the Titan disk (Appendix C), which might be sufficient to detect limb darkening or brightening, but not much in the way of detailed structure. In the far-ultraviolet region, both cameras are hampered by the red sensitivity of the detectors, particularly the charge-coupled devices (CCD) used by the WF/PC. The ultraviolet filters have relatively poor transmission and appreciable out-of-band transmission, particularly in the red. Moreover, the far-ultraviolet emissions (e.g., of H, N, C, N₂, and H₂) originate mainly in the exosphere of Titan, excited by interaction with charged particles trapped on magnetic field lines of Saturn.

Second is spectroscopy of Titan between 1000 and 3000 Å. A study in the ultraviolet range at medium and high resolution would be the best way to search for the spectral signatures of the photodissociation products of organic molecules that may be present in the atmosphere. The advantage of the HST, relative to previous ultraviolet satellites such as the IUE, will be a higher spectral resolution and a higher sensitivity (Titan is too faint to be observed with IUE below 2000 Å). The instruments to be used would be the faint-object spectrograph, for a medium-resolution spectrum of the whole ultraviolet range, and the high-resolution spectrograph, for investigating specific spectral signatures at high spectral resolution using different modes (depending upon the wavelength and the lines to be searched for). However, at this stage it is not clear whether either of these two spectrographs has sufficient sensitivity to detect any species other than the dominant atoms and diatomic molecules of the outer atmosphere of Titan.

Many complex organic molecules exhibit strong vibration-rotation lines in the infrared and rotational transitions in the far-infrared, submillimeter, and millimeter ranges. These lines cannot be observed from the ground. Moreover, in the case of a weak source such as Titan, the background noise is very strong. A cooled instrument in space, like SIRTf or ISO, is needed to perform the observations. An alternative solution is to observe Titan in the millimeter range with a heterodyne system and long-baseline interferometer. This is certainly a ground-based program to be developed in the near future. However, in the millimeter range, rotational transitions, under the excitation conditions of planetary atmospheres, are usually much weaker than transitions corresponding to higher J values, i.e., in the submillimeter and far infrared. The search for complex molecules on Titan with ISO, SIRTf, and LDR thus appears to be a promising method, complementing ground-based millimeter programs. Molecules to be searched for include the following nitriles: CH₃CN (acetonitrile), C₂H₅CN (propionitrile), C₂H₃CN (acrylonitrile), and possibly adenine. The instruments to be used would be high-resolution spectrometers with a spectral resolving power as high as possible; however, at long wavelengths (>50 μm) the observations will have to separate Titan from Saturn—i.e., will have to be performed with the best possible angular resolution when Titan is near elongation. Initially, SOFIA may offer the superior resolution needed and have the sensitivity to detect at least the strongest features.

A quantitative inventory of organic compounds and their distribution with altitude within the atmosphere may illuminate the specific production mechanisms responsible for their existence. At the moment, such mechanisms are largely matters of theoretical speculation. Detailed atmospheric observations will also contribute to an understanding of the aerosols and surface materials that have accumulated over the age of Titan.

Suggestions for Further Reading

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3.5 Comets

Comets are especially interesting as frozen remnants of the primordial solar system. As such, they might provide clues needed to understand the subsequent evolution and differentiation of the planets and their satellites following the initial condensation of the solar nebula. Was there something special about the conditions in the early evolution of the solar nebula that created the terrestrial planets at the right distance from the Sun so that at least one of them was able to chemically evolve life? In addition, the comets themselves may have contributed substantially to the inventory of volatiles and organics available to the primitive Earth. We can estimate the rate of cometary impacts early on from the cratering histories of the Moon and Mars, but we need to know the abundance and probable structure of the biogenic elements within the comets to know how much they might have affected the earliest phases of abiotic chemical evolution on Earth. Three of the basic questions to be answered are

1. What are the compositions and structures of comets?
2. Where and how were they formed?
3. Did they contribute volatiles and/or organics to Earth?

While specialized missions that approach or penetrate particular comets may yield the most precise chemical information, such missions sample only one comet at a time. To understand the global characteristics of the early solar nebula will require a large statistical sample of cometary properties. Such data can be collected only by remote observational surveys. What is learned from these observations may well influence the detailed design of individual future cometary missions such as CRAF. There will necessarily be much indirect inference associated with remote cometary observations, but that does not reduce their importance.

Following the extensive studies of comet Halley, and in the interim period before another major comet mission, the first problem can now be approached only with models based on phenomena observable by optical and radio techniques. In particular it is possible to differentiate and study the coma and tail when the comet is at small heliocentric distances, while an unresolved asteroid-like inactive nucleus is all that is accessible for comets at several astronomical units from the Sun.

The generally accepted cometary model of an icy conglomerate a few kilometers in diameter containing both volatile and refractory components was first proposed on the basis of an analysis of the "nongravitational" force perturbations of the orbit of periodic comet Encke. These forces arise from the jet action produced by the nonuniform vaporization of matter from the surface of a rapidly rotating comet nucleus. Subsequent investigations have concluded that the major volatile component controlling the vaporization must be water ice, and recent ultraviolet spectra of a number of comets provide strong confirming evidence for this idea. Not only is water ice confirmed as the dominant volatile in the nucleus, but an initial composition of volatiles similar to what is found in interstellar molecular clouds appears to be needed to account for the observed abundances of visible radicals. In a different approach, which ignores the details of the chemistry and simply counts the end-product atoms that are then assembled into a hypothetical nucleus, water ice again emerges as the dominant constituent.

Unlike planetary atmospheres, which are gravitationally bound and exhibit only relatively mild temporal variations, the atmosphere of a comet is a highly transitory and variable phenomenon. The most rudimentary coma models assume that the parent molecules sublime at the surface of the nucleus and flow radially outward, subject only to the solar particle and ultraviolet radiation fields that progressively decompose them into their constituents atoms (or ions), which continue to flow radially outward. Although rudimentary, this one-dimensional picture serves as a basis for derived abundances of H, O, and OH in the coma that appear to be consistent with an H₂O source that is at least an order of magnitude more abundant than any other hydrogen-bearing molecule. For comet Halley the spacecraft measurements verified this predominance of water.

The fundamental compositional differences between comets, as deduced from ground-based observations, is the dust-to-gas ratio. This is related to the amount of observed continuum radiation (sunlight reflected from solid grains) relative to gas fluorescence produced by C₂, C₃, CN, etc., which is taken as a measure of the total gas production rate. Among the species detectable in the visible (which represent less than 1% of the total volatile component), there appears little variation from comet to comet, provided that observations are compared at similar heliocentric distances. The abundance of these species relative to H₂O (or at least to OH presumably derived from H₂O) is also relatively constant from

comet to comet. One exception does exist, and that is CO^+ , whose fluorescence in the comet-tail band system in the blue gives the ion tail its visibility. This species is often absent from the coma, and no ion tail is seen, particularly in old, short-period comets. On the basis that spectacular ion tails are most often associated with bright, new comets, and that both CO and CO_2 are considerably more volatile than H_2O , it has been suggested that new comets contain a significant fraction of either of these species and that, for at least a part of their orbit, the sublimation of gases from the nucleus is controlled by this more volatile fraction.

Spectroscopy in the far-ultraviolet provides a convenient means of studying compositional variations of the dominant volatile species. H_2O , CO_2 , and CO all have signatures in this spectral region, as do the dissociation products of H_2O (H, O, and OH), as well as C, C^+ , CO^+ , and CO_2^+ . Several sulfur compounds also fluoresce in the far-ultraviolet, including S, CS, and the recently discovered diatomic sulfur, S_2 . Since the terrestrial atmosphere is opaque to wavelengths below 3000 Å, observations in the far-ultraviolet have to be made from above the absorbing O_2 and O_3 .

In May 1983, comet IRAS-Araki-Alcock (1983d) passed to within 0.032 AU of the Earth, providing a unique opportunity to study the structure of a cometary coma on a scale of tens of kilometers from the ground and from Earth orbit. A major contribution of the IUE satellite observatory was the discovery of S_2 in a region ~ 500 km around this comet. The spatial distribution and the expected photochemical lifetime of S_2 imply that it is produced directly from the nucleus at $\sim 10^{-3}$ the rate of water molecule production. Furthermore, the short lifetime makes this species an ideal tracer of short-term cometary activity. IUE data on S_2 obtained over a 32-hour period have shown a marked temporal variation that can be associated with the visual Sunward "fan" of this comet. The presence of S_2 in cometary ice is also potentially an indicator of the physical conditions prevalent at the time of the formation of the comets (or "cometesimals") in the solar or pre-solar nebula. S_2 is generally much reduced in abundance relative to other sulfur polymers in the gas phase at low temperatures. The significance of S_2 will not be fully appreciated until its presence in other comets is confirmed in future ultraviolet observations.

The successful encounter missions with comet Halley in March 1986 (Giotto, Vega, and Suisei) and the plethora of Earth-based observations carried out during this apparition have served to largely confirm the aforementioned models of the cometary coma. It is still too early to draw any significant conclusions from the images of the nuclear region of comet Halley regarding the mechanism of dust and gas ejection (or sublimation) from the dark nucleus, but the *in situ* measured chemical composition of both the gaseous and solid components of the coma was found to be consistent with what was expected on the basis of remote observations of comets performed over the past decades. Water, the dominant constituent, was also detected remotely using very-high-resolution

interferometric spectroscopy at $\sim 3 \mu\text{m}$ from the KAO, illustrating the potential of this technique in the future for the detection of other parent molecular species. Surprisingly, neither the *in situ* measurements nor the remote ultraviolet observations have reported the presence of any gaseous chemical species previously unknown in comets. However, there has been a report, from low-resolution infrared spectroscopy, of the detection of spectral features due to organic compounds in the cometary grains, but this interpretation remains highly controversial. Unfortunately, the *in situ* dust analyses cannot resolve this question since they could measure only the atomic constituents of the dust particles; molecular bonds were broken upon impact of the dust on the instrument because of the large velocity of the spacecraft relative to the comet. Nonetheless, a significant fraction of the small particles consisted almost entirely of the biogenic elements, C, H, O, and N, in various combinations. These results are very preliminary, and much detailed information about the gas and dust in the coma is expected after further analysis of the wealth of comet Halley data. However, it seems likely that new information will emerge to encourage further remote study of biogenic elements in future comets, particularly “new” comets which are of most interest in this regard.

The infrared range is the best spectral region for analyzing micrometer-sized particles, typical of cometary dust, wherein may be found the majority of the biogenic elements and compounds that could be incorporated into the early Earth by cometary impact. Several observations can be considered:

1. Mapping of the dust between 1 and 18 μm at moderate spectral resolution ($\lambda/\Delta\lambda \sim 100 - 1000$). The instruments to be used are infrared cameras with medium-resolution filters. The scientific objectives in mapping the dust are

- a. Searches for the silicate signature at 10 and 18 μm .
- b. Searches for the signatures of O-H, C-H, and C-C bonds in the 1- to 7- μm region in order to recognize organic and carbonaceous dust grains as well as the hydrated phases. Data from the Giotto mission to Halley point strongly to the existence of carbon-rich or entirely carbonaceous grains.
- c. Search for an icy halo at 3 μm (in the very center of the coma).
- d. Constraints upon the size and the composition of the dust, by analyzing the general shape of the thermal flux between 4 and 18 μm .

2. Observations of cometary dust at longer infrared wavelengths (20–200 μm). The shape of the spectrum beyond 20 μm is very sensitive to the size of dust particles. An accurate measurement of the slope of the spectrum between 20 and 200 μm would provide new constraints, especially for the large particles.

3. Observations of the coma with the high spatial resolution from LDR. Eventually, LDR and/or FIRST will provide the possibility of directly observing the primary constituents of the coma after they have been sublimated from the nucleus. H_2O could be easily detected and mapped at 557 GHz.

All these observations will be complemented by continuing ground-based observations at microwave frequencies. The potential for extremely high spatial resolution using interferometers may prove to be valuable in interpreting the lower-spatial-resolution infrared data, and distinguishing between several possible parent species and production mechanisms.

Just as the infrared is best suited to studies of cometary grains, the ultraviolet is the spectral region in which the most abundant atoms and small molecules fluoresce. The primary objectives, therefore, of Space Telescope observations of comets would concentrate on the photochemical evolution of the gaseous component of the inner coma. There are few spectral signatures of simple organic molecules in this part of the spectrum so that the presence of prebiotic molecules must be inferred from observations of the spatial distribution of dissociation products resulting from photochemical decomposition of the heavier molecules. Observations of comets made over the past 6 years using the IUE satellite have provided a wealth of new information about the chemistry and evolution of the inner coma. These studies will be strongly enhanced with the use of ultraviolet spectrographs on both HST and ASTRO.

Suggestions for Further Reading

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3.6 Asteroids and Meteors

Most of the 3500 asteroids for which orbits are known circle the Sun between Mars and Jupiter and are found between 2.1 and 3.2 AU. In addition to this main belt, there are important classes such as the Trojans at the L_4 and L_5 points of the Sun-Jupiter system and the near-Earth asteroids such as the Amors, Apollos, and Atens. The largest of the asteroids (1-Ceres) is about 1000 km across while the smallest for which physical data are available have diameters of only 500 to 1000 m.

Because of their small size it has been common to impute dull geological histories to the asteroids as a group, but considerable evidence against such a view can be marshalled. In particular, it has been demonstrated that at some time during its 4.5-billion-year history, the asteroid 4-Vesta was hot enough for lavas to have erupted onto its surface.

On the basis of reflectances, colors, and other optical properties it has been possible to divide asteroids into several groups. The most abundant of these are the S-types (reflectances near 0.15 and colors similar to those of ordinary chondrites) and the C-types (very low reflectances, often less than 0.05, and colors

similar to carbonaceous chondrites). By the mid-1980s more than half a dozen "types" had been identified and their distributions charted as a function of distance from the Sun. In part, the observed pattern has been interpreted to reflect the temperature gradient believed to have controlled the condensation of solids in the early solar nebula. For instance, in accordance with such a model the probably more volatile-rich and carbonaceous objects are relatively more abundant at distances farther from the Sun than the asteroid belt.

A major breakthrough during the past decade has been the development of two techniques for the routine determination of diameters (and therefore, reflectances). These radiometric and polarimetric techniques have been verified in several instances in which asteroid diameters could be obtained directly from observations of stellar occultations. As a result, the average diameters of hundreds of asteroids are known reasonably well, as are the average absolute reflectances of their surfaces. A complication arises in that many asteroids are known to have irregular shapes (as deduced from observed periodic fluctuations in their brightness).

Asteroids are seen as distant point objects from Earth, and any compositional information is derived from measurements of how their surfaces scatter sunlight. Such spectral-reflectance techniques have been developed extensively over the past two decades. Characteristic absorption features make it possible to identify some key minerals, and although matching is not always exact, a striking correspondence between the spectra of certain asteroids and some meteorites has been established. The lack of precise matching must have several causes. First, there are measurement uncertainties in both the asteroid and the meteorite data. Second, and more importantly, it is very unlikely that meteorites provide a full sample of surface materials present in the asteroid belt. Finally, it must be realized that asteroid surfaces have undergone long histories of space weathering, whereas space-weathered samples of meteoroid surfaces are not available for laboratory measurements. In spite of such difficulties, it has proved possible to characterize the likely compositions of many asteroid surfaces and to examine the distribution of various compositions as a function of distance from the Sun. In most cases spectral-reflectance measurements are restricted to the global properties of asteroid surfaces, although careful observations made at different phases of an asteroid's rotation period have recently documented evidence of variations in composition on the surfaces of a few asteroids such as 4-Vesta and 8-Flora.

Spectral-reflectance measurements provide data on surface composition only; they contain no direct information on the internal makeup of the body. Such information can sometimes be inferred from an accurate measurement of the mean density. Unfortunately, approximated masses have been determined from orbital perturbations for only four asteroids so far, and the determination of additional masses must await close spacecraft flybys. Such flybys will also provide accurate measurements of volumes, and will represent a future source of very precise density determinations for asteroids.

One known difficulty with spectral-reflectance measurements is that it can be difficult to derive uniquely and accurately the relative abundances of key constituents if one does not know *a priori* the whole suite of materials present and the texture of the regolith. This problem is especially acute when dealing with the abundances of optically opaque materials (metallic nickel/iron, magnetite, carbonaceous material). This is a major contributing factor to disagreements in the literature over the metallic content of S-asteroid surfaces and the relationship of dark asteroids such as Pallas to carbonaceous chondrites.

One major question concerns the types and distributions of organic-rich and volatile-rich materials that formed in the solar system as a result of direct condensation from the solar nebula or aggregation from primitive presolar dust, or subsequent processing on or within parent bodies. Several types of parent bodies are involved—main-belt asteroids, Trojan asteroids, small satellites of the outer planets, and comets. Each population of parent body has experienced its own long history of evolution and it is difficult to infer the original characteristics from what we observe today. Is any interrelationship that we observe representative of that which obtained in the early stages of the solar system? A particular difficulty is that our only compositional information on distant objects comes from remote-sensing data that refer only to the surfaces of these bodies. How do we relate the surface composition to internal bulk characteristics or to the detailed properties of meteorite samples measured in the laboratory?

One important investigation would involve a concerted effort to define the inventory of carbonaceous materials in the solar system, as a prelude to determining its precise composition and ultimately its provenance and history. From the study of meteorites it is clear that several types of carbonaceous materials are present. Some of this material has undergone evident processing on parent bodies and it is suspected that most of these parent bodies were asteroidal rather than cometary in origin. Whether or not any carbonaceous meteorites could be derived from comets remains an issue of current debate.

Spectral-reflectance measurements in the near infrared have made it possible to identify certain asteroid surface materials with carbonaceous meteorite analogs: for example, 1-Ceres has been associated with a CI or CM carbonaceous chondrite. It is evident from such observations that the surfaces of C-asteroids in the main belt vary in the strength of the 3- μ m absorption feature attributed to water-of-hydration in the clay minerals that make up these materials. In general, such measurements are difficult to make and require high sensitivity and high resolution. Since it appears possible to relate the strength of the 3- μ m feature to carbonaceous meteorite mineralogy, an important goal of asteroid research should be to establish how widespread such material is and to determine the strength of this feature for as many C-asteroids as possible.

The carbonaceous material associated with asteroids in the outer solar system is different spectrally from that in many of the bodies in the asteroid belt. A distinction has been made between the C-material in the main belt and the D-material (very dark, but redder) that is found in the outer fringes of the

main belt and at the orbit of Jupiter. Evidence has been presented that the carbonaceous materials in comets might be similar to this D-material. The spectral characteristics of the D-material have been defined poorly, and high-resolution spectrometry in the infrared would help constrain its composition and test available speculations concerning its nature. There is a tendency to regard D-material as a less "processed" version of what becomes C-material, but such vague suggestions need to be tested.

A fundamental question in dealing with carbonaceous material in the solar system concerns the possible interrelationship of comets and some types of asteroids. It has long been suspected that some comets must evolve into objects resembling Earth-crossing asteroids. Two recent observations have added circumstantial support to this general view. The first was the discovery by IRAS of a small, asteroid-like body (1983 TB) whose orbit is closely similar to the Geminid meteor stream. The second was the discovery of disturbances in the solar wind that might be attributed to the release of volatile material from the Apollo asteroid 2201-Oljato. Several Earth-crossers have been identified as likely dead comets on the basis of their orbital characteristics. Thus, an important problem is how to identify the dead comets among the population of Earth-crossers (from orbital or remote-sensing observations) and then to obtain high-resolution spectra of their surfaces for comparison with meteorite samples and other solar system small bodies. Another opportunity for understanding the interrelationships may arise from a study of meteor showers.

Current measurements of the properties of comets constrain the abundances of volatile materials; the refractory component abundances must be inferred by other means. This may be possible from measurements of the ultraviolet spectra of meteor showers associated with active and extinct comets. Because many meteors are too fragile to survive passage through the Earth's atmosphere, such spectroscopic measurements are the only method by which elemental abundance ratios for a large number of known cometary samples can be determined. Ground-based optical efforts have not been sufficiently quantitative because of the large number of iron lines that mask other interesting features. There are several "iron-free" windows in the ultraviolet (1150–1250 Å, 1300–1350 Å, 1370–1550 Å, 1800–1900 Å, 1970–2080 Å) through which lines of H, C, SiO, P, S, N, O, Al, Mg, Mn, Ca, Na, and Zn may be strong enough to be visible from low-Earth-orbit observations of meteor streams. If practical, such observations might be conducted from a dedicated instrument launched from the Shuttle or an ELV, or from one of the polar-orbiting platforms associated with the Space Station composed primarily of Earth-observing instruments. This may provide additional data to combine with inventories of meteoritic abundances and help identify the dead cometary component among the Earth-crossing asteroids.

A summary of important measurements to be taken and questions to be answered follows:

1. High-spectral-resolution infrared (1 to 5 μm) spectra of C-asteroids and

related objects such as D-asteroids and comets should be obtained.

2. A comprehensive survey of the strength of the 3- μ m water-of-hydration feature in the spectra of dark asteroids should be carried out.

3. The 3.3- to 3.5- μ m region indicative of C-H bonds in organic matter should be searched.

4. The relationship of meteorite samples to asteroid parent bodies and to contemporary asteroids (especially for the more volatile-rich types) should be determined.

5. The provenance of Earth-approaching asteroids should be determined. (How can we distinguish between the asteroid-derived population and the cometary one?)

6. What clues about the makeup of parent bodies can be inferred from studies of cosmic dust collected in the Earth's upper atmosphere and from meteor investigations?

These measurements will not of themselves be sufficient to decipher the historical connection between asteroids and comets, but they will be helpful adjuncts to the necessarily limited number of flybys that are now being planned by NASA, ESA, and the Soviet Union.

Suggestions for Further Reading

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3.7 The Protosolar Nebula and its Analogs

The protosolar nebula represents a critical boundary between the local chemistry and processing of the biogenic elements and compounds and the rather ubiquitous organic chemistry that is observed in a large number of interstellar and circumstellar regions. The formation of the protosolar nebula was an energetic process, and the fundamental question is how the energetics affected the preexisting complex chemistry. From our studies of primitive solar system bodies we may be able to infer the distribution of the biogenic elements and compounds early in the history of the solar nebula. It is doubtful whether we will discover a timekeeper of sufficient precision to be able to distinguish between the possibility that the deduced distribution of chemical complexity arose *ab initio* from an elemental mixture within the protosolar nebula, or was imposed upon it by the processing history within the cloud from which it formed. For this reason it is extremely important to search for analogs of the protosolar nebula evolving today within regions of active star formation. The organic chemistry within and without the nebula must be compared in detail to decide whether the material from whence planets might eventually form retains

a memory of the gas phase and grain surface chemistry that had been slowly accumulating within the parent cloud. Whether complex organic chemistry originated early in the history of the solar system or arrived from elsewhere will profoundly influence the likelihood of life arising elsewhere. Analogs of the protosolar nebula are critical to our understanding.

Stars form through the gravitational collapse of interstellar molecular clouds. This process starts with the fragmentation of the parent cloud into a number of clumps, many of which may collapse to form stars. According to present models, the initial collapse phase is isothermal, but when the cloud becomes opaque to visible radiation it heats up. Since the initial cloud is rotating, the cloudlet will flatten during the collapse. The core collapses faster than the outside, resulting in a core-envelope structure, with the envelope falling freely onto the core. The core itself consists of a central object (the protostar) in hydrodynamical equilibrium surrounded by an accretion disk (the protoplanetary disk). The core is separated from the envelope by an accretion shock. In this accretion shock,

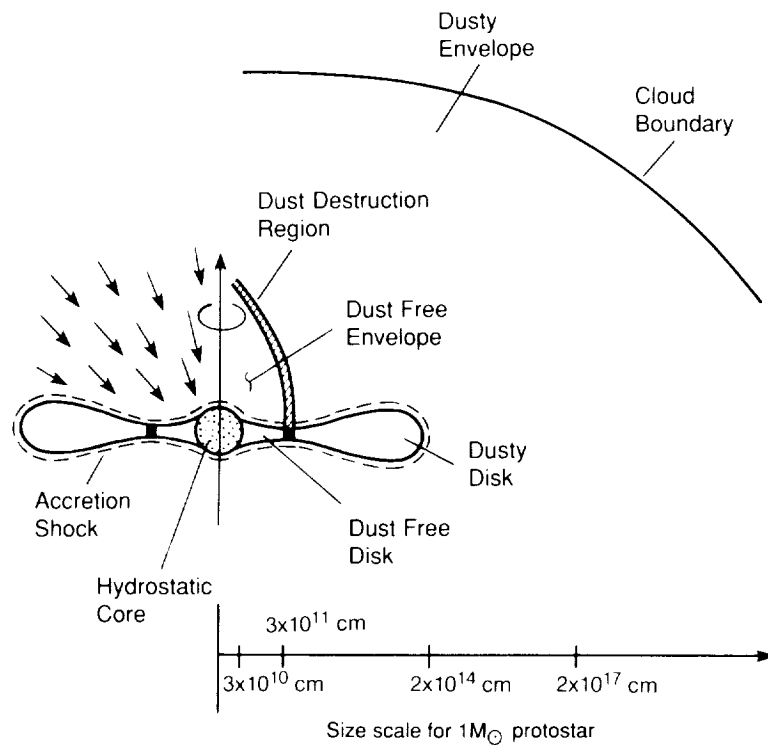


Figure 3-4. The different regions in a collapsing, rotating interstellar cloud.

nearly all of the kinetic energy of the falling envelope is transformed into internal energy of the gas and radiated away. For a central object of approximately one solar mass, the shock velocity on its surface is about 300 km/sec, while the shock luminosity is about $40 L_{\odot}$. There will also be an accretion shock in the disk, with a range of velocities depending on the position within the disk. However, the main heating of the disk is thought to be viscous heating driven by turbulence. Close to the central object the dust initially present in the collapsing envelope will have been vaporized by the strong radiation field generated by the shock, creating a dust-free zone. The different zones in a collapsing, rotating interstellar cloud are illustrated in figure 3-4, which shows the typical sizes for these zones.

This global picture of star formation has recently been modified with the discovery of strong stellar winds from protostars. The effect of the protostellar wind on the molecular cloud is thought to cause two shocks. First, the wind will shock against the shell of swept-up material (i.e., the wind shock, <400 km/sec). Second, this shell of swept-up material will be driven supersonically into the surrounding molecular cloud material ($v \sim 15$ km/sec). The size of the wind-acceleration zone is about protostellar size or perhaps the size of the circumstellar disk. The size of the wind shock and the molecular cloud shock is much larger, possibly even larger than the size of the collapsing envelope. This is shown in figure 3-5.

Carbon monoxide observations in the vicinity of pre-main-sequence stars reveal blue-shifted and red-shifted emission in two opposing lobes. The observed outflow velocities around T Tauri stars (pre-main-sequence stars with $M \sim 1M_{\odot}$) are about 15 km/sec or less. Emission from shocked, vibrationally excited H_2 has also been detected in these regions. The most spectacular sign of outflow from protostars is, however, the phenomenon of Herbig-Haro (HH) objects. These nebulae show a strong emission-line spectrum due to cooling behind the shocks. Proper motion studies and optical line studies reveal space velocities of up to 400 km/sec. The proper motion vectors of the HH objects in a family point back toward the exciting star. These shocked clumps of gas are either ejected directly from the circumstellar disk of the protostars, or they may represent the interaction between the directed flows from these objects and their molecular cloud environment. It is believed that the responsible stars are the precursors of even the T Tauri stars, which themselves are pre-main-sequence stars. The evolution of the protosolar nebula is thus envisaged to incorporate phases of both infall and outflow, possibly simultaneously. The importance of the HH-exciting stars is twofold: first, they indicate hitherto unsuspected violent activity around the protostar, and second, their study reveals clues to the physical and chemical nature of protostellar disks and circumstellar nebulae.

Both the nebular morphology of the HH objects themselves and their proper motions, where these can be determined, indicate that the outflows from their exciting stars are highly anisotropic. The flows are either unipolar or bipolar

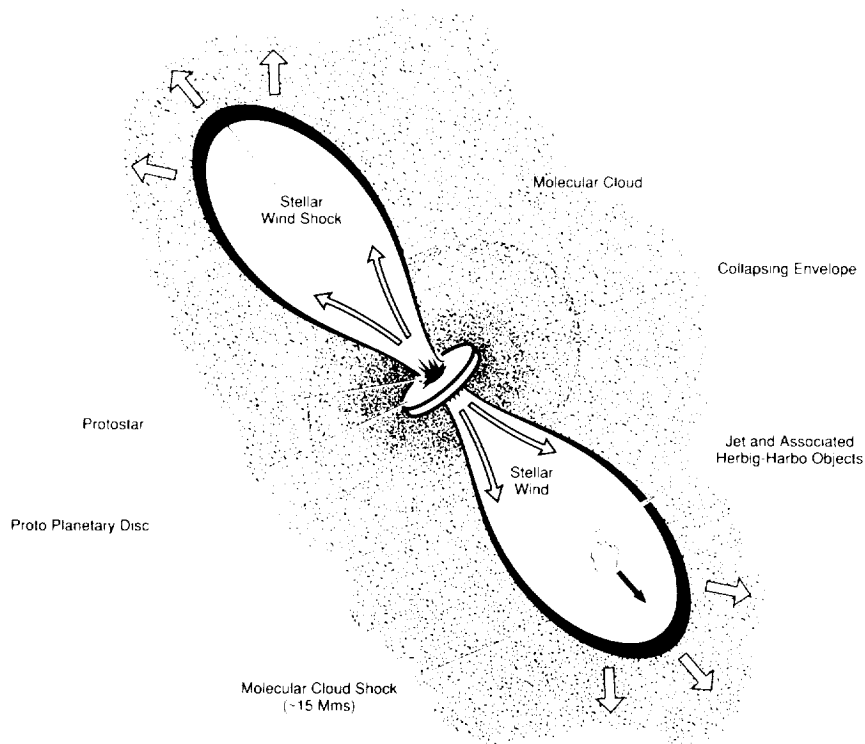


Figure 3-5. Schematic of a stellar wind-driven shock model of a protostar.

with oppositely directed velocity fields. Some even show evidence for precession (i.e., the gradual rotation of the axis of outflow with time). In a few cases the HH objects can be traced back, essentially to the ejecting stars, in the form of well-collimated “jets.” In two cases, a radio jet continues to the star from the nearest HH object. Stellar binarity is reasonably well established for two systems and may be important in others, but the mass ratios of these binaries are totally unknown. The inferred (projected) orbital planes of these binaries are orthogonal to the flow direction from the system. Airborne far-infrared measurements for a number of HH-exciting stars have resolved the emitting regions at 50 and 100 μm orthogonal to the flow direction. But even the smallest far-infrared beam sizes obtainable with the present airborne observatories are unable to resolve these regions in the flow direction. The emitting regions have radii of about 10^3 to 10^4 AU and presumably they represent the flattened, collapsing

envelope of the protostar. The mass in these regions is difficult to estimate from the far-infrared observations because the dust properties are essentially unknown. Moreover, these observations probe only the dust and not the gas, which makes up most of the mass. Ground-based aperture-synthesis observations of the gas through molecular line transitions in the millimeter range will be forthcoming. Although such observations can yield much insight into the dynamics of these systems, mass estimates will still be difficult, because the dominant component of the gas, molecular hydrogen (H_2), cannot be observed this way.

T Tauri stars are newly formed stars as evidenced by their high lithium abundance, their high rotation velocities, and their general association with dark clouds. Their ages, as estimated from their position in the Hertzsprung-Russell (HR) diagram, range from about 10^5 to 10^7 years. T Tauri stars are often surrounded by a circumstellar disk. As inferred from statistics, these disks are presumed to have a large radius-to-thickness ratio and they give the impression of a continuous transition in the morphology of protostellar nebulae from the very earliest protostellar stages (the HH-exciting star), through the pre-main-sequence stars (the T Tauri stars), to the main sequence, where protoplanetary "disks" may be detected. Recent studies indicate that T Tauri stars are very active and exert a significant influence on their environment. Besides the strong stellar wind mentioned before, X-ray and chromospheric emission have been detected, indicating strong flare activity on the protostellar surface. All T Tauri stars may undergo the FU Orionis phenomenon (a major stellar eruption) during their evolution.

Among the T Tauri stars, the object HL Tau is a keystone. It is currently the only T Tauri star to show ice absorption in its circumstellar shell. It also exhibits the strongest silicate absorption feature at $10\ \mu\text{m}$ and the greatest degree of visible linear polarization. Polarimetric, near-infrared images indicate a flattened, extended object on a scale of 10^2 AU. The star shows HH object nebulosity as well as an extended streamer or jet. All of these characteristics point toward the presence of a flattened dust distribution close to the exciting star, possibly a dusty disk. In the HR diagram, HL Tau is located at the top of the convective track for a $1-M_\odot$ star, with a stellar age of about 10^5 years. HL Tau may therefore provide an ideal analog for the protosun at age 10^5 years.

Estimates of the column density in small particles provide a lower limit to the mass of dust that is consistent with the far-infrared estimates of $1\text{--}6 \times 10^{-5} M_\odot$. Much more material might be hidden at the much smaller scale size than presently resolvable, or the gas in the immediate vicinity of HL Tau may have already condensed into solid grains and accreted into undetectable large (centimeter-sized) particles.

Understanding the formation of stars and planets and the distribution and composition of matter (particularly the biogenic compounds) in protostellar nebulae is a topic for exobiology. This includes studies of the physical and

chemical conditions in the collapsing envelope, the formation and evolution of circumstellar disks and protostars, and the interaction of the protostellar wind with the collapsing envelope and the parental molecular cloud. A study of these questions as a function of age of the protostar, coupled with information on the effects on biogenic materials from these environmental factors and the corresponding role of biogenic compounds in the collapse process (e.g., as cooling agents), could provide general constraints on the origin of life in other solar systems. In particular, an important question to answer is that of the relative time scales for planet formation, the origin of life, and the decay of the eruptive activity of star formation. It should be repeated here that objects such as HL Tau may provide excellent analogs for studying the early stages of formation of the solar system and the study of astrophysical boundary conditions on the origin of life in planetary systems.

Although there is secure theoretical support for this global picture of star formation, the observational evidence is rather limited. Astronomers lack an adequate observing tool. In particular, as evidenced by Appendix C, a resolution of about 0.01 arcsec is required to resolve planet formation in the dusty disk around protostars in the Taurus dark cloud, the nearest site of star formation (see fig. 3-3). Such resolution will not be available in the near future. However, a permanent manned presence in Earth orbit, along with construction capabilities, raises the possibility of large arrays of orbiting telescopes. These could easily have baselines capable of resolving planets at 1 AU from their stars. Over the longer term, observing facilities could be placed at a lunar base.

Detailed studies of collapsing protostars with sufficient spatial and spectral resolution to decipher the chemical and kinetic variations inflicted on the biogenic elements and compounds as a function of time is essential to understanding whether the formation of a protoplanetary system similar to our own protosolar nebula is a common occurrence in the universe. Further, having formed a protoplanetary system, it is also critically important to understand whether the final stages of the star-formation processes in the center of the nebula have any significant influence over the planet-formation process, and/or the early history of the newly formed planetary surfaces and atmospheres. Observationally, we have recently understood that the star-formation process is far from quiescent, even for the low-mass stars similar to our Sun. What is yet unknown is when the precise epoch of planetary system formation occurs in relation to the energetic outflows and HH object formation and acceleration and the existence of a very large rotating disk system of molecular gas and dust. And how do these various phenomena affect the newly formed planets? What are the signposts of systems that are about to form planets versus those that have already formed planets versus those that never will? Will these planets be like the assemblage in our own solar system? What is the distribution of raw materials from which they can form? In time it may be possible to detect and spectroscopically examine planets in orbit about other stars, as well as any debris left over from the formation of

the planets, but until that time, studying the precursors of the planetary systems and using them as analogs for understanding our own solar nebula may help us to assess the potential for life sites elsewhere in the universe.

During the collapse phase, the opacity in the collapsing envelope is very high in the visible and near-infrared. Essentially, one can hope to see the central object and the dusty disk only in the far-infrared and submillimeter. Fortunately, many molecules, atoms, and ions have transitions in these wavelength regions. Poor atmospheric transmission in these wavelength regions mandates observations from Earth orbit. The LDR will be a good instrument for the study of the collapse phase of star formation. The LDR, with a 20-m aperture, can achieve a resolution at 100 micrometers of about 100 AU for protostars in the Taurus cloud, sufficient to resolve the collapsing envelope. Studies of molecular rotational transitions can then yield important chemical, spatial, and kinematic information on the collapsing envelope and the interaction of the outflow with the circumstellar envelope. High spectral resolution ($\lambda/\Delta\lambda = 10^5$) is required for such studies. Such high resolution is also required to provide velocity discrimination across the accretion shock on different parts of the protoplanetary disk and on the central object, as well as to study the interaction of the outflow with the circumstellar disk and with the parent molecular cloud. Important lines for these studies are the far-infrared, fine-structure transitions of CII, OI, and OIII, the high-lying rotational transitions of CO, and the rotational transitions of HD and H₂.

Important information on the kinematical structure of the collapsing envelope and the outflow, and their interaction, can also be obtained from near-infrared absorption-line studies. Molecular vibrational transitions are particularly useful, because the detailed rotational structure can be used to derive excitation temperatures and total column densities. This may aid in relating potential multiple components spatially. Such studies have already been performed for the luminous, massive protostar in Orion. With a cooled telescope from Earth orbit (e.g., SIRTf and ISO) this also will become possible for less-luminous, less-massive protostars, such as T Tauri stars. High spectral resolution ($\lambda/\Delta\lambda = 10^5$) is imperative to resolve the rotational structure.

The HST may provide an excellent platform to observe protostars during the latter phases of the collapse, when the envelope has been dispersed by the strong stellar wind. Its high spatial resolution and good ultraviolet sensitivity will allow studies of HH objects and jets much closer to the photospheric surface than presently possible. The ultraviolet lines of high ionization stages of C and O are useful diagnostics for the shock conditions (e.g., pre-shock density, shock velocity). The 0.1-arcsec resolution of the WF/PC on the HST corresponds to about 10 AU at the distance of the Taurus cloud. This is probably still insufficient for spatial resolution of the actual acceleration zone of the stellar wind, yet the question of precisely where HH objects originate may be amenable to study from the HST. By imaging through narrow-band filters that isolate specific

shock-cooling emission lines and using the HST's high ultraviolet spatial resolution, one might hope to trace details of the HH flows into the immediate stellar vicinity using their characteristic shock lines. These observations might bear at least indirectly on the issue of confinement of HH flows by circumstellar disks. Examination of the "base" of an HH flow might serve to determine whether a mechanism similar to a solar coronal hole is operating near the protostellar pole or whether the confinement and orientation of these flows arises some distance above the stellar surface.

A crucial question, of course, relates to the nature of those stars that are known to drive HH flows or jets. It is believed that they are the precursors of even T Tauri stars, but they are often so deeply embedded in dark clouds that they are not directly visible, optically. One technique for studying their photospheres is to investigate the spectrum of scattered starlight from circumstellar clouds and nebulae. This method has begun to bear fruit, optically, and it could certainly be extended into the ultraviolet with the HST.

Polarization studies on this scale may also yield important information on the structure of the circumstellar disk, through the asymmetrical scattering of starlight by grains in the disk.

Recent work with the IUE has demonstrated that variable ultraviolet absorption lines occur in the spectrum of Beta Pictoris. These lines are thought to arise in the circumstellar disk detected in the infrared around this star. Such spectra could be obtained with the HST for a much larger sample of candidate stars around which IRAS observations indicate the potential presence of dusty disks.

SIRTF and ISO will be able to detect the infrared continuum emission from low-mass protostars throughout the galaxy, although their relatively large beam size in the far-infrared (~ 30 arcsec), where most of the luminosity is emitted, will present some confusion problems for distances of about 10 kpc or larger. LDR will be able to detect low-mass protostars to a distance of 100 kpc. This includes, besides our own galaxy, the Large and Small Magellanic Clouds.

SIRTF and ISO could provide diffraction-limited, two-dimensional imaging of near-infrared starlight scattered by disk particles. Because of its larger aperture size, SOFIA could improve upon these telescopes for far-infrared studies of the collapsing envelope. In particular, because of the increased spatial resolution, one might hope to resolve all dimensions of the collapsing envelope. Such studies will also be helped by the advent of new detector technology (e.g., the development of linear and fully two-dimensional detector arrays designed to oversample the Airy disk, thereby producing the spatial resolution close to the theoretical limit).

Suggestions for Further Reading

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3.8 The Detection of Other Planetary Systems

One major goal for exobiology is to determine the distribution of potential sites for the emergence of life in the universe. Since life as we know it is a planetary phenomenon, this means detecting and surveying extrasolar planetary systems as well as systems where planets are about to form or where planets have failed to form. It is of particular interest to discover whether the general characteristics of our solar system, with its trio of early water-bearing planets, bombarded by organic-rich meteorites and comets, are repeated frequently in other systems. We may be able to make great progress in understanding why Venus and Mars apparently contain no extant life by comparative planetology studies within our own solar system alone. However, to the extent that the limitations on life involved the cosmic environment of these two planets, other planetary systems must be studied to assess how probable the sets of conditions favorable to the formation of life really are in the universe.

There is currently no unambiguous evidence for the existence of any planetary system outside the solar system. Recent advances in ground-based instrumentation have resulted in the detection of large disks of dust and gas surrounding nearby stars. Nonetheless, evidence for extrasolar planetary systems is still lacking. Star-formation theory predicts that planets will abound, but none has been found, only the intriguing clues. This is perhaps not too surprising; until recently, the measuring tools available were woefully inadequate for the discovery of all but the most massive planets around the nearest stars. On more than one occasion, the classical ground-based observational programs have resulted in exciting discovery claims of one or more planets orbiting familiar stars, such as Barnard's star. However, more recent measurements with modern photoelectric detectors negate these earlier discoveries and illustrate how difficult it is to fully account for all the systematic biases that may develop as equipment ages in a dynamic environment under the influence of 1 Earth gravity. The opportunities for stably orbiting long-lived instrumentation above the Earth's atmosphere in the near future promise to revolutionize this situation.

There are four different ways to search for extrasolar planetary systems; all are complementary and all will probably be necessary to detect and study all the members of another system. Of these four methods, three will derive great benefit from orbiting instrumentation which will remove the performance limitations imposed by the atmosphere. Definitive results can be expected within the decade, and spectacular successes are possible if dedicated systems can be afforded.

How do you detect another planetary system? Given sufficient angular resolution and the ability to detect a very faint object in contrast to a very bright object, one might hope to directly image extrasolar planets at optical or infrared wavelengths. The task is extremely difficult. To detect Jupiter in orbit about the Sun, if the system were at a distance of 10 parsecs (33 light-years), requires the ability to distinguish two objects whose relative brightness is 2×10^{-9} and

whose apparent separation is 0.5 arcsec. For the Earth/Sun system, at 10 parsecs, the contrast ratio is 2×10^{-10} and the separation on the sky is only 0.1 arcsec. Contrast ratios in the infrared may be less severe for the giant planets, and in general smaller, fainter stars make the contrasts more favorable. The primary limitation for ground-based systems is that the atmosphere spreads out the image of a star over a circle that is at best 0.5 arcsec in diameter, inhibiting the discovery of any close-in orbiting planets. Planets in larger orbits will reflect less starlight and thus be intrinsically fainter and more difficult to detect with any imaging device.

There are also three indirect methods for deducing the presence of planetary mass companions in orbit about nearby stars. The first measures the reflex motion of the star resulting from the fact that both stars and planets orbit about a common center of mass. This orbital motion introduces a tiny "wobble" into the space motion of a nearby star when measured against the more distant fixed stars. Astrometry is the attempt to accurately measure the relative position of a star over decades in order to uncover this small periodic displacement. To infer the presence of Jupiter in orbit about a solar mass star at a distance of 10 parsecs requires the position of the star to be measured with an accuracy of 0.3 milliarcsec, while an accuracy of 1 microarcsec is required to detect the influence of Earth. With extreme care and modern instrumentation, ground-based observatories can achieve an accuracy of 1 milliarcsec by combining many observations over a period of months. The atmosphere imposes an absolute limit of 0.1 milliarcsec, but long-term systematic changes in the telescope itself may prevent this limit from being achieved. Unlike direct imaging, astrometric measurements must be continued over time scales comparable to the orbital periods of the planets in order to verify that the detected wobble has the expected periodic shape.

If the orbital plane of the planets is nearly perpendicular to the plane of the sky, two other indirect detection techniques are possible. The orbital motion about a common center of mass can be detected because of the periodic Doppler shift it introduces into the spectrum of the star. An emission or absorption line from the atmosphere of the star will be blue-shifted as the star approaches the observer and red-shifted as the star recedes along its orbit. Searches based on these shifts in the wavelength of the stellar lines are called spectroscopic, and this is the method of detection that is least disturbed by atmospheric attenuation and turbulence. Great precision in measuring the change in the wavelength is required over periods comparable to planetary orbit time scales. Great precision is currently being achieved from the ground. This method is nearly independent of the distance to the star, provided that the star is sufficiently bright. The effects of a Jupiter-sized planet in orbit about a large number of relatively nearby stars should be discernible from the ground, but the searches have been under way for only a few years and there are not yet enough data. Terrestrial atmospheric effects will preclude the detection of the smaller wavelength shifts

introduced by an Earth-sized planet and some, as yet unknown, but quasi-periodic fluctuation in stellar atmospheres themselves may impose a more stringent limitation on this technique.

The last detection method, called "photometric," is statistical. If the orbital plane is favorably inclined, then the luminosity of the star may be observed to decrease slightly every time the star is occulted by one of the orbiting planets. The event is short-lived and unpredictable because of the unknown inclination of the orbital plane and the phases of the planets when the measurements are begun. Thus many stars must be monitored continuously with precision sufficient to detect a change in stellar luminosity of 10^{-6} in each of two broad-band colors, so that fluctuations in the stellar emission can be distinguished from the real eclipse events. Ground-based studies of new instrumentation for this technique are just beginning, and it is not yet clear whether the required technology can be achieved.

The HST is unlikely to achieve the earlier advertised contrast ratio of 2×10^{-7} at a separation of 1 arcsec at visible wavelengths, and its usefulness for direct imaging of planetary systems is dubious. It is more likely to be of greater use in the study of the larger and more extended precursors to planetary systems (see section 3.7). However, if time can be obtained, this instrument may be able to search a handful of nearby stars or follow up on other indications of planetary systems; a systematic survey is unlikely given the enormous demand for observing time. The second generation of HST instrumentation will include one of two infrared instruments currently being developed competitively, either a near-infrared camera (NICMOS) or an imaging Michelson spectrometer (IMS). Neither is ideal for planetary detection, but they do open up the wavelength region with the most favorable contrast ratios for the giant planets. Evaluation studies of the HST optics and the imaging performance of these two instruments should be closely watched by the exobiology community to attempt to ensure that the superior planet detector is selected. ISO and SIRTf will operate in the infrared, and have been discussed as possible opportunities for imaging nearby planetary systems. Although their sensitivity will be extremely good, both telescopes lack the required spatial resolution. The proposed "superresolution" capability requires signal-to-noise ratios that are probably greater than those provided by a faint planet. The prospects for direct imaging of a large number of planets in the near term do not look hopeful.

The HST will also have two instrument systems that can make astrometric measurements. Neither will improve on the current ground-based accuracy and neither will be available for the extensive observing time needed for multiple observations over the decades required to discern the systematic stellar motion. The single best near-term candidate instrumentation for a systematic search for extrasolar planetary systems is a dedicated imaging astrometric telescope mounted on the upper boom of the Space Station. NASA's Task Force on the Scientific Uses of the Space Station has recently concluded that it should be

possible to build an orbiting astrometric telescope, associated with the manned Space Station, which would be capable of positional accuracy of 10 micro-arcsec on stars in limited areas of the sky for periods as long as 10 to 20 years. This accuracy exceeds current ground-based performance by two orders of magnitude. With such a capability it would be possible to detect, with some assurance, planets like Uranus around the nearest few hundred stars, and Jupiter-like systems would, if they exist, be easily found. A reasonable statistical sample of other planetary systems could be developed with an astrometric telescope in orbit, or very meaningful limits could be placed on their existence.

As already stated, spectroscopic searches for extrasolar planetary systems are little affected by the atmosphere. As long as the apparent brightness of the star is great enough, this technique can provide exactly the same capability to find planets orbiting distant stars as it can for nearby ones. Systems with the required stability to recognize the periodic wavelength shifts induced by a Jupiter-mass planet already exist; detection of the smaller shifts induced by terrestrial-type planets will ultimately probably be limited by the atmosphere. Current ground-based efforts are now limited by the lack of detailed information about the presence of any long-term periodic or quasi-periodic changes within the stellar photospheres that could mimic or mask the planetary velocity signature. It seems quite likely that this technique will begin to pay off consistently in the near future.

Photometric searches capable of monitoring 4000 stars continuously in two colors with an absolute precision in the luminosity determination of 10^{-6} might detect about one planet per month. Most of the detections will be the short-period planets, and planets as small as Earth may not be detectable during the active phases of the stellar cycles. A number of technological obstacles must be overcome before this technique can be demonstrated. This may eventually be possible with instrumentation proposed for the Block II Space Station; work is beginning on the required technology. Photometry could prove to be an especially critical technique for studying the distribution of mass and orbits in other planetary systems, since it works best for the short-period inner planets, unlike the other approaches.

In contrast to photometry, the opportunity for making an early start on an orbiting astrometric telescope has never been clearer or more promising. An orbiting manned Space Station would ensure that the necessary orbiting superstructures will be available to allow the development and operation of a dedicated astrometric telescope at very low cost in a reasonable time. The manned Space Station is a key element for a number of reasons. First is an ability to perform consistent on-orbit maintenance and service, which will ensure that the system can operate consistently over the required time. Second, although the telescope system should be designed for largely routine, automatic operation, there would no longer be a requirement for it to be completely autonomous, thus reducing the cost substantially. Third, on-orbit integration with the Space

Station would relieve any requirement that it be transported to orbit in a fully integrated way. Finally, the Space Station will provide a stable platform from which to conduct observations for the decades that are required to accomplish a systematic astrometric search of a large number of stars. Because the stellar position is measured only relative to the reference stars in the surrounding field, and not absolutely, an astrometric telescope is uniquely immune to nearly all of the mechanical perturbations introduced by manned use of the Station. It is therefore one of the few astronomical tools that can be considered for an attached payload—the most cost-efficient way to interact with the Space Station.

In the hopeful event that planets begin to be identified around nearby stars, the next task will be to attempt to discern whether some form of life might exist there. New technologies and a new generation of dedicated orbital instrumentation would be required to tackle this problem. Some very preliminary suggestions have been made; they require either an interferometer or a very large single aperture operating at visible wavelengths. If the separation of the ~ 1 -m elements of the interferometer can be maintained to within 10^{-6} cm for periods of ~ 100 hours, then it should be possible to image the atmosphere surrounding the distant planet and spectroscopically detect the ozone band near 6800 Å, assuming the concentration of ozone is similar to the very large non-equilibrium (biologically generated) value of the terrestrial atmosphere. Requirements on the surface accuracy of a large monolithic mirror greatly exceed those achieved for the HST. If such a mirror quality can be achieved and combined with occulting masks that suppress the bright stellar image, similar searches for O₂ and ozone could be conducted. Near-term ground-based studies should begin on these or any other approaches to explore the potential for developing the technologies required to meet what today appear to be impossible specifications.

Suggestions for Further Reading

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3.9 Molecules in Space

There are two reasons for the relevance of interstellar chemistry to exobiology. First, the presence of large amounts of fairly complex organic molecules (up to at least 13 atoms in size) in interstellar clouds raises the question of what the limit is to the complexity attainable by interstellar molecules. Second, if

complex molecules are synthesized in the interstellar medium, the question of the possible connections between the existence of these species and the existence of biological molecules on Earth is of interest. The first of these questions can be addressed by both theoretical and observational approaches. It is feasible to discuss whether the theoretical models predict large abundances of yet-to-be-detected complex molecules, whether observational techniques can locate such complex molecules if they exist in appreciable abundance, and what the best frequencies and observational tools might be. The second of these questions is very difficult to answer. The processes of star and planet formation from collapsing interstellar clouds are not yet understood in any detail. An understanding of the chemical relationship between organic interstellar molecules and those on newly formed planets such as the primeval Earth requires an understanding of the physical conditions experienced by the molecules during the transitions from interstellar cloud to protosolar nebula and comets, from protosolar nebula to planetesimals, and from planetesimals and comets to planets. (Some of these issues are addressed in other sections of this report.) We will discuss answers to the first of the two questions only. In addition, we will briefly discuss small molecules of exobiological interest—chief among these is water.

Interstellar clouds are giant accumulations of gas and dust particles that exist primarily in the planes of the Milky Way and other spiral galaxies. Typical temperatures in these clouds range from 10 to 100 K except in localized star-forming regions, which are considerably warmer. The matter is mainly gaseous, with perhaps only 1% (by mass) in the form of small dust particles, or grains, roughly 0.1 μm in radius. The density of the gas in a typical, dense, interstellar cloud is in the range 10^4 to 10^6 cm^{-3} ; that in the so-called diffuse interstellar clouds is typically in the range 10^{-1} to 10^2 cm^{-3} . The major constituents of the gas are molecular hydrogen (H_2) and helium. Molecules involving heavier atoms, of which close to 70 are known, possess lower abundances by significant factors. With respect to H_2 , the (fractional) abundance of CO in dense clouds is typically 10^{-4} ; that of water, as large as 10^{-5} ; that of methanol, 10^{-7} ; and that of even more complex species 10^{-8} to 10^{-10} . The molecules range in complexity from diatomics such as H_2 and CO up to a 13-atom, linear, unsaturated nitrile (HC_{11}N) and include many of the better-known small organic molecules. Note that even though the detected molecules involving heavy atoms are trace constituents of a rarified gas in the clouds, the clouds are so vast that the amount of organic matter in them surpasses that on Earth.

The mechanism by which gaseous molecules in dense interstellar clouds are excited into emission in the microwave region of the spectrum is predominantly inelastic collisions. These collisions convert translational energy into rotational energy, promoting one of the collision partners into an excited rotational state that then emits as it relaxes to a lower rotational level. In the bulk of interstellar clouds, there is insufficient thermal energy to populate excited vibrational states via inelastic collisions. Consequently, vibrational emission, which would be

detected in the infrared, can be seen only in selected hot regions such as star-forming areas. Vibrational spectra can sometimes be seen in absorption if there exists a suitable continuum infrared source such as hot dust surrounding a star embedded deep in the cloud. Nevertheless, practical difficulties in the use of ground-based infrared astronomy, such as atmospheric interference, have heretofore relegated this technique to a distant second place behind radio astronomy in the observation of gaseous interstellar molecules.

The two important *in situ* mechanisms for the production of complex gas-phase molecules in dense interstellar clouds are synthesis from atoms and smaller molecules by reactions on the surface of dust grains followed by desorption into the gas or by reactions in the gas phase. Both of these mechanisms have been studied in some detail. In general, it has been difficult to determine whether gas-phase reactions or grain-surface reactions are more important, although the former are currently favored. Quantitative, time-dependent treatments that contain calculated abundances of large molecules have been undertaken for both the grain-surface mechanism and for the gas-phase mechanism. These calculations involve sizable numbers of molecules and reactions, but terminate at species of rather small size in the context of biology. It is possible to simplify the computational problems involved in these models and still obtain agreement with observation. In particular, a "semidetailed" steady-state treatment of the gas-phase chemistry in the dense interstellar cloud TMC-1 can account for the abundances of organic hydrocarbons as complex as methyl acetylene (C_3H_4) or the radical C_4H . Unfortunately, extension of even this treatment to larger molecules is hindered by a lack of rate-coefficient data for important reactions. As these data are obtained in the laboratory, the semidetailed treatment can be extended to include larger molecules. A still more approximate solution of the kinetic equations has been utilized to estimate how efficient gas-phase reactions are in producing complex interstellar hydrocarbons. In this approach, hydrocarbons through 12 carbon atoms in size have been considered.

A severe upper limit to the abundances of complex hydrocarbons in the gas phase can be obtained from cosmic-abundance arguments. Assume that the total fractional hydrocarbon abundance (with respect to the gas density) in the gas phase of dense interstellar clouds is about 10^{-4} . This is approximately the total fractional carbon abundance and is itself probably an upper limit. Also assume that the total abundance of all hydrocarbons with n carbon atoms is a factor of a times the abundance of all hydrocarbons with $n-1$ carbon atoms where $0 < a < 1$. This assumption is clearly an idealization, but it is hard to imagine the abundance of all hydrocarbons with n carbon atoms increasing as n increases for a significant range of n . According to a variety of theoretical treatments, the fractional abundance of 1-carbon hydrocarbons, f_{C_1} (mainly methane), is 10^{-6} . Then a is equal to 0.99, and complex hydrocarbons possibly can have high abundances. For example, the fractional abundance of 12-carbon hydrocarbons would have an upper limit of 9.0×10^{-7} . Thus, the use of cosmic-abundance

arguments and a constant multiplicative factor a do not lead to stringent limits on the abundances of complex hydrocarbons unless the total cosmic abundance resides in the smallest hydrocarbons (i.e., f_{C_1} approaches 10^{-4}).

The abundance of hydrocarbons produced by gas-phase reactions has been estimated using the approximate kinetic model mentioned previously. With this model, the total fractional abundance of all 12-carbon-atom hydrocarbons is approximately 10^{-10} , far below the upper limit we have developed here. The semidetailed treatment extends only to 4-carbon-atom hydrocarbons. A crude extrapolation of these data leads to predictions that $f_{C_{12}}$ is somewhere in the range 10^{-9} to 10^{-11} , in good agreement with the former hydrocarbon estimate. So it would appear that despite great uncertainties, approximate and semidetailed gas-phase theoretical treatments “predict” abundances far below the cosmic-abundance-derived upper limits. The detailed grain-surface treatment is a time-dependent model, as is the detailed gas-phase model. The use of these models to extrapolate complex hydrocarbon abundances will lead to answers that depend on the age of the interstellar cloud. In the gas-phase model, abundances of hydrocarbons are maximized at intermediate cloud lifetimes (10^5 to 10^6 years) well before steady state is achieved. Extrapolation of calculated abundances at such lifetimes leads to higher estimates than extrapolations based on the semidetailed model. However, an estimate of the minimum time necessary to synthesize such complex hydrocarbons via gas-phase reactions yields an answer of approximately 10^7 years, far longer than the time at which the smaller hydrocarbons exist at maximum abundance, thus throwing doubt on the extrapolations. The grain-surface treatment, on the other hand, shows smaller hydrocarbons with high abundances at a time as large as 10^7 years. Extrapolation of these results yields a value of $f_{C_{12}}$ below 10^{-12} .

It is difficult to conclude much at all from these extrapolations other than that they yield complex hydrocarbon abundances significantly smaller than upper limits based on cosmic-abundance arguments. Increased measurements of important rate coefficients will enable the heretofore successful gas-phase semidetailed treatment discussed above to be extended to much larger species.

What do current observations tell us about the abundances of very complex molecules in dense interstellar clouds? A broad infrared feature at $3.4\ \mu\text{m}$ has been interpreted as indicative of complex organic matter on the surfaces of grains. Likewise, other broad infrared features have been interpreted as indicative of a wide variety of unresolved polycyclic aromatic hydrocarbons in the gas phase. However, our best extrapolations based on distinctive, sharp, gas-phase microwave spectra involve the linear cyanopolyynes, HC_nN , where n is an odd integer. In the well-studied source TMC-1, HC_3N , HC_5N , HC_7N , HC_9N , and HC_{11}N have been observed. Their abundance drops by a factor of approximately four each time two more carbons are added from $n = 5$ through $n = 9$. With a fractional abundance of 10^{-8} for HC_5N , simple extrapolation using this factor yields a fractional abundance of approximately 6×10^{-13} for the

hypothetical interstellar molecules HC_{19}N . This rather large result is in reasonable agreement with the extrapolation of the successful gas-phase semidetailed calculation to $f_{\text{C}_{20}}$ (10^{-11} to 10^{-15}) only if we assume a synthetic bias toward linear, unsaturated species. The number of possible 20-carbon hydrocarbons is quite large and encompasses many different types of skeletal branching. If many of these species have abundances similar to the estimated abundance of HC_{19}N , then our large cosmic-abundance-determined limit may indeed be appropriate. However, the gas-phase mechanism favors highly unsaturated species. If this mechanism is operative, according to current opinion, then the large abundance of HC_{19}N is in line with our extrapolation of the semidetailed calculation. Despite this agreement, we are forced to conclude that there is indeed great uncertainty in trying to estimate the abundances of complex hydrocarbons and, by extension, all other complex organic species based on the limited, present-day observations. It seems reasonable to suggest that our knowledge of the abundances of these species in dense interstellar clouds based on microwave observations will increase gradually and incrementally as species slightly larger than those previously seen are detected.

What are the prospects for observing species more complex than HC_{11}N ? Consider the spectral region currently utilized by radio astronomers; this extends roughly from 1 to 300 GHz, with the lower frequencies labeled microwaves and the higher frequencies labeled millimeter waves. Studies of the radiation physics of emission lines in this spectral region show that for each molecule there is an optimum emission frequency, or frequency of maximum emission intensity, which is a function of both temperature and the size of the molecule. As temperature increases, the optimum emission frequency increases as the square root of temperature. As the size of the molecule increases, the optimum emission frequency decreases dramatically. As an example, for a linear hydrocarbon with 20 carbon atoms in a cool interstellar cloud ($T = 10$ K) the optimum emission frequency is about 5 GHz, whereas in a warm cloud ($T = 50$ K) this frequency rises to about 11 GHz. If the calculations are performed to maximize the observed signal-to-noise ratio, this latter frequency falls to 8 GHz, because the noise level of the receiver increases with frequency. This example shows that the detection of complex molecules via rotational transition frequencies is best attempted at microwave and millimeter rather than submillimeter wavelengths.

However, there is a fundamental problem in observing complex molecules via rotational transitions at any frequency. As molecules become more complex, their density of rotational states increases, typically (for linear molecules) as the cube of the number of heavy atoms. This means that the number of molecules in any given rotational level decreases dramatically as the number of atoms increases. The intensity of an emission spectral line is proportional to the number of molecules in a given energy level. Hence, the intensity of any specific emission line decreases strongly as the number of atoms increases, because the emission is spread out into many more emission lines. In particular, a linear

hydrocarbon with 19 carbon atoms will have its emission line of optimal frequency reduced in intensity by a factor 300 from a linear hydrocarbon with 3 carbon atoms, assuming the species have the same dipole moment and the same abundance.

Although these considerations suggest that observing more complex molecules in the interstellar medium via microwave and millimeter studies will be difficult, it is possible that other wavelength regions may provide a better method of detecting these molecules. Studies in the infrared region can be conveniently divided into low-resolution and high-resolution investigations. High-resolution studies can be used to study gas-phase interstellar molecules in both absorption and emission. Low-resolution studies can be used for both the gaseous and condensed phases. Emission studies in the infrared require a warm or nonthermal (e.g., shocked) portion of an interstellar cloud, whereas absorption studies require a suitable background continuum source. At first glance it would appear that infrared observations avoid the severe problems encountered in the microwave and millimeter ranges caused by the dilution of rotational states of complex molecules since the density of vibrational levels of complex molecules is quite low even for very complex species, at least at low excitation energies. This apparent advantage versus rotation cannot be realized in high-resolution studies because gas-phase molecules rotate as well as vibrate and a high-resolution infrared transition involves a change in the rotational, as well as the vibrational, quantum state. Low-resolution infrared studies avoid this problem of rotational fine structure, but at the expense of facile identification of the emitting or absorbing species. To minimize the rotational fine structure, it would be desirable to study molecules in absorption at the lowest possible excitation temperatures and densities in order to minimize the excitation of rotational levels. Unfortunately, most theories of interstellar chemistry do not predict significant abundances of complex molecules in low-density, diffuse clouds. In addition, the Doppler broadening caused by large-scale rotation within the clouds may blend the closely spaced lines together and make them unresolvable even with ultrahigh-resolution infrared spectroscopy. However, high-resolution infrared studies will be beneficial for smaller emitting or absorbing species in the gas phase once the practical difficulties of this type of astronomy are overcome by space observatories such as SIRTf.

It would thus seem that infrared studies at lower resolution offer our best hope for complex molecule observation. However, the difficulty of identifying the carrier of a low-resolution spectrum can be great. Consider the broad, 3.4- μm feature which has been explained by varieties of organic matter on dust surfaces, but has also been claimed to be due to bacteria. Or consider the tentative, but hardly unambiguous, identification of gaseous polycyclic aromatic hydrocarbons via broad features at 6.2 and 7.7 μm . Perhaps the best that can be hoped for is the functional group analysis used by organic chemists who observe

a low- or medium-resolution infrared spectrum of a complex molecule and deduce what functional groups and/or bonds the molecule possesses. This type of analysis utilized for interstellar spectra would not yield specific molecules, but would indicate the types of complex molecules present. Any organic molecule would be expected to show a C-H stretch at 3.38 to 3.51 μm , an olefinic hydrocarbon could show a C=C stretch at 5.95 to 6.17 μm , an alcohol could show an O-H stretch at 2.75 to 2.79 μm , etc. A special area of investigation that may hold unusual promise is the spectra of complex molecules in the far infrared (over 50 μm or less than 6 THz); far-infrared spectra correspond to low-frequency vibrational transitions, which are often more precise indicators of the specific species than are the higher-frequency vibrations. Whether this specificity would remain under low resolution is unclear at present in large part because of a lack of spectroscopic data in this region of the spectrum. The best-studied far-infrared spectrum is probably that of methanol, in which it arises from a so-called torsional motion. Torsional spectra of many other simple species still remain to be studied in detail in the laboratory.

It has been suggested that the well-known diffuse bands, seen in the visible and ultraviolet as starlight passes through diffuse interstellar clouds, are due to complex gas-phase organic hydrocarbons, specifically C_n species with $n > 5$. Although it is unclear how complex molecules can be efficiently synthesized under the low-density conditions of diffuse clouds, it is worthwhile to pursue this line of reasoning. The claim is that long-chain C_n molecules might be able to withstand photodissociation via the interstellar radiation field that penetrates into diffuse, but not dense, clouds. Instead, the molecules manage to utilize the energy they receive from an absorbed photon to internally convert from one state to another until they re-emit the excess energy and avoid dissociation. The internal conversion process leads to a finite width for the excited states of the molecules, which is supposed to cause the diffuseness of the visible bands. Also, as discussed earlier, a new variant of this claim has been made that links the diffuse bands with polycyclic aromatic hydrocarbons (PAHs) and suggests the width of the features to be due to the unresolved rotational fine structure. These claims should be investigated in some detail because if they are at all valid, they represent a manner of specifically detecting complex species via line width. What must be understood are the precise spectra of these species, their photodissociation rates in the diffuse interstellar medium, and the source or sources of the large spectral widths.

Theoretical models of interstellar chemistry in the future should include significantly more complex molecules than have heretofore been the case. This is especially true of gas-phase models because many ion-molecule laboratories are currently measuring relevant rate coefficients. The semidetached approach to chemical modeling offers the best opportunity for making predictions of the gas-phase abundances of complex species.

Observations from above the atmosphere are needed for a number of small molecules in both diffuse and dense interstellar clouds. Not only are observations of molecules of direct exobiological interest such as H_2O and O_2 needed, but many other molecules whose study is important to obtain an understanding of the chemical and physical conditions in interstellar space are unobservable from the ground.

The unambiguous observation of increasingly complex molecules in the interstellar medium will not be achieved easily. Difficulties exist in every region of the electromagnetic spectrum considered. In the realm of radio astronomy, the most likely wavelength region appears to be at low frequencies. These frequencies do not require telescopes on satellite platforms, but are quite accessible from the Earth. Certainly, as current receiver technology improves, it should be possible to extend the size of the molecules currently detected in the microwave range. In addition, it might be possible to detect functional groups of complex species or even the species themselves via low-resolution infrared spectroscopy, and even visible and ultraviolet studies will be significantly enhanced via space-based observatories such as HST, SIRTf, and LDR. The more complex the organic chemistry detected in interstellar clouds, the more interesting the interstellar medium becomes to exobiologists.

Suggestions for Further Reading

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3.10 Interstellar Dust

Small, solid particles (dust) must have played an important role in determining which biogenic compounds were incorporated into the early solar nebula and at which stage of chemical processing. The exact role dust played cannot be understood until the nature of interstellar and circumstellar dust has been determined. Was dust the bulk source of carbon? Was the dust siliceous but coated with an icy organic mantle? What volatiles were trapped within grains? How big were the grains before and after passage through the accretion shock? Collected specimens of interstellar dust particles and remote observations of many physically different environments may answer these questions. Interstellar dust can be studied through its interaction with electromagnetic radiation by measuring

the extinction, the linear and circular polarization, and the scattering of nebular and star light. Interstellar extinction and polarization curves have been determined for numerous stars with diffuse interstellar material along the line of sight. The observed extinction and polarization curves can be used to determine grain sizes if their composition (i.e., optical constants) is known. However, very little information of this sort is available for dust in molecular clouds.

The dust can also be studied through its interaction with the gas, although it is difficult to extract information on the dust from these data. For example, the dust may significantly influence the molecular composition of the gas, but because of the difficulty in disentangling gas-phase and grain-surface reactions only H_2 is unambiguously attributed to grain-surface reactions.

Finally, the dust can be studied indirectly by determining the depletion of the elements in the gas phase with respect to solar abundances. In such an approach it is generally assumed that the missing elements are locked in solid dust grains. Correlations between the observed depletions and physical parameters, such as condensation temperature, may then lead to insight on the specific composition and condensation history of the dust grains.

Despite 50 years of active research, the composition of interstellar grains is still highly uncertain. Most researchers in this field agree that silicates and some form of carbon are present. The detection of the 10- and 20- μm features (presumably the Si-O stretch and O-Si-O bend in silicate materials) in a large variety of objects points toward the ubiquitous presence of silicates in the interstellar medium. The composition of the carbonaceous component is, however, more controversial. Some researchers think that the carbon is mainly in one or another highly condensed form, based on the strong 2200- \AA peak in the interstellar extinction curve, which can be attributed to $\sim 200\text{-}\text{\AA}$ nearly spherical carbonaceous grains. In such a model it is assumed that larger ($\sim 1000\text{-}\text{\AA}$) carbon grains are also present, which then produce a large fraction of the visible extinction. A small fraction of the visible and the far-ultraviolet extinction, and the visible polarization, is produced by silicate grains with sizes in the range of 100 to 2500 \AA . Inside molecular clouds these grains can accrete molecular mantles consisting of simple molecules such as water, ammonia, and carbon monoxide, plus all the other possible condensable interstellar molecules. But in the diffuse interstellar medium these grain mantles are presumably quickly removed by photodesorption and sputtering in low-velocity shocks. Good observational evidence exists for the presence of icy grain mantles inside molecular clouds and for the absence of water ice grain mantles in the diffuse interstellar medium.

In an alternative model, the carbon is mainly in the form of large molecules in grain mantles on silicate cores. Some carbon ($\sim 25\%$) is still in some highly condensed form, in order to explain the 2200- \AA peak. The bulk of the visible extinction and polarization in the diffuse interstellar medium, however, is due to these grain mantles. The molecular mantles are presumed to be formed by ultraviolet photolysis of the simple molecular mixtures accreted on the silicate grains

in molecular clouds. The more complex molecules produced by the ultraviolet photolysis of the simple molecules in the mantles are more refractory than the simple ices and therefore can better survive in the harsh environment of the diffuse interstellar medium. These processes can be studied in the laboratory, and preliminary results of such studies indicate the ultraviolet photolysis can be important in the evolution of interstellar dust. Some observational support for the presence of complex molecular-grain mantles in the diffuse interstellar medium exists.

Models for the formation of the dust are likewise controversial. The refractory grain materials, such as silicates and the carbonaceous grains, are presumably formed at high temperatures (100–2000 K) in the carbon-rich or oxygen-rich outflow from late-type red giants, supergiants, planetary nebulae, novae, supernovae, and protostellar nebulae. The detection of large infrared excesses supports the picture of grain condensation around late-type red giants, supergiants, and planetary nebulae. No unambiguous observational evidence exists yet for the condensation of dust around supernovae. The primary locations for the condensation of grains composed of the biogenic elements is one of the questions that the exobiology community would like to answer. As discussed earlier, the complex grain mantles are presumed to be formed after the condensation process, when the grains have been cycled within molecular clouds in the interstellar medium.

Little is known about the actual dust condensation process in the outflow from stellar objects. Observations typically lack the spatial resolution required to resolve the condensation zone, while experiments and theory are hampered by the lack of knowledge of the relevant physical conditions in these regions. Condensation possibly occurs in thermodynamic equilibrium with the most refractory material condensing into small nuclei onto which somewhat less refractory materials condense out sequentially when cooling nuclei reach the condensation temperature of those materials in the outflow. Alternatively, condensation might take place under highly supersaturated conditions and all materials might then condense out more or less simultaneously into an amorphous material. Since grains offered the best opportunity for biogenic molecules to become incorporated into the protosolar nebula, it is most important to understand the composition and elemental inventory of grains in distinct locales. Of particular interest is the incorporation of trace constituents, which have been detected in meteorites (e.g., ^{26}Al and S-process Xe) into this stardust. These tracers may allow the nucleosynthetic history of the parent grains to be reconstructed.

Finally, another important characteristic of grains, their distribution, is also highly dependent on the condensation process. In particular, is coagulation important for the formation of large grains? Obviously, large fluffy conglomerates of small particles may have quite different physical properties (surface area, strength, extinction properties) than large homogeneous particles.

It is appropriate to single out infrared spectroscopy because of its great potential for remote sensing of dust material. Infrared spectroscopy is a powerful tool for the study of the composition of interstellar dust. Broad absorption features appear superimposed on the infrared continuum of many interstellar sources. Because of their spectral width, these features are generally attributed to molecular vibrational transitions in solid materials.

A molecular group (such as the methyl group, CH_3) absorbs at a few characteristic vibrational frequencies. The peak frequency and absorption strength of such a group does not vary much between different molecules within a given class of molecules (such as saturated hydrocarbons). This makes the identification of molecular groups (and classes of molecules) from observed infrared spectra relatively easy. It does, however, somewhat hamper the precise identification of the specific molecule involved in the absorption or emission process. Precise identification can be rendered even more difficult by the presence of a collection of molecules and the possible overlap of their absorption bands. The detection of rather subtle spectral variations and thus relatively high-spectral-resolution studies ($\lambda/\Delta\lambda > 10^3$) are needed to identify specific molecules. Fortunately, identification can be assisted by studying the spectra of a large sample of sources and correlating the spectral variations with the physical conditions in these sources.

The possibilities and pitfalls of infrared spectroscopy of interstellar grains will be illustrated with two examples: interstellar grain mantles and large molecules.

Ground-based observations around $3\text{ }\mu\text{m}$ have confirmed the presence of water ice in grain mantles inside molecular clouds through the detection of the $3.08\text{-}\mu\text{m}$ OH-stretching vibration. Evidence for the C-H bond stretch has also been found in the 3.2- to $3.6\text{-}\mu\text{m}$ band. The detection of other features, in particular the carbon-bearing molecules, is hampered by atmospheric absorption in the 5- to $8\text{-}\mu\text{m}$ region and the presence of the strong ice and silicate bands, which dominate the 3- and $10\text{-}\mu\text{m}$ regions, respectively. Airborne or spaceborne observations of the 5- to $8\text{-}\mu\text{m}$ region of the spectrum are therefore extremely important to determine the composition of interstellar grain mantles.

Figure 3-6 shows the 5- to $8\text{-}\mu\text{m}$ spectrum of the bright, protostellar object W33A obtained with the KAO. Deep absorption features at 6.0 and $6.8\text{ }\mu\text{m}$ are apparent. The $6.0\text{-}\mu\text{m}$ band can be identified with the bending mode in water ices, reinforcing the identification of the $3.08\text{-}\mu\text{m}$ band with the OH-stretching mode in water ice. A good agreement is obtained with the spectrum of pure water or mixtures of water and other molecules as long as the concentration of water is greater than 50%. The $6.8\text{-}\mu\text{m}$ band is at the correct wavelength to be the C-H deformation mode in saturated hydrocarbons. A comparison of the observed spectrum with that of methanol (CH_3OH) shows reasonable agreement (fig. 3-6). Higher-resolution observations are needed to confirm this identification by detecting the subtle variations in the $6.8\text{-}\mu\text{m}$ band, as present in the methanol spectrum. The position and shape of the $6.8\text{-}\mu\text{m}$ band show that

unsaturated hydrocarbons—such as aromatics, alkynes, and simple aliphatic ketones—are not dominant in interstellar grain mantles along the line of sight toward this object. The 5- to 8- μm spectra of other objects do suggest the presence of such molecules in the grain mantles in those regions.

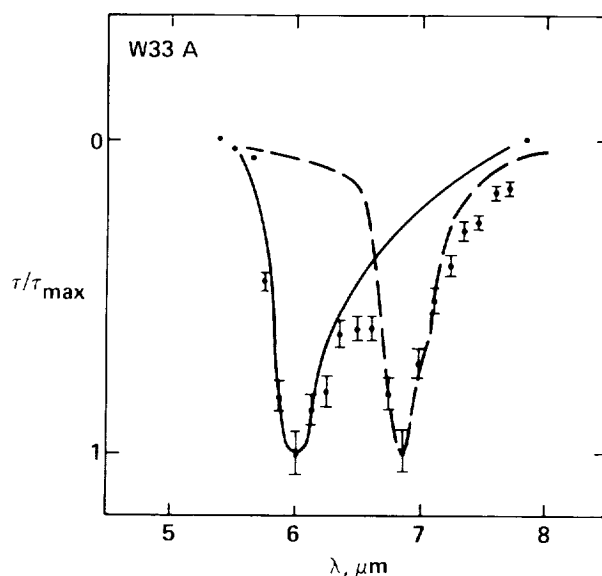


Figure 3-6. The 5- to 8-micrometer spectrum of the bright, protostellar object W33A obtained with the KAO.

Many celestial objects show infrared emission features at 3.3, 3.4, 6.2, 7.7, 8.6, and 11.3 μm . Some researchers have attributed these features to ultraviolet-pumped infrared fluorescence from a collection of PAHs. In particular, the 3.3- and 6.2- μm features point strongly toward fundamental vibrations in aromatic ring molecules. A particularly striking Raman spectrum from a collection of such molecules (auto exhaust) is compared in figure 3-7 with the 5- to 10- μm spectrum of the emission features in the Orion bar. The close agreement between the Raman spectrum and the interstellar spectrum is strong circumstantial evidence that they arise from similar groups of species, since Raman-active and infrared-active modes are similar in frequency and number in these molecules. The number of carbon atoms in the emitting molecules, derived from the observations, is about 50. The abundance of these species is estimated to be about 2×10^{-7} of that of hydrogen. If this interpretation of the infrared emission

features is correct, then about 1% of the elemental carbon is locked up in these species. It is noteworthy that the carbonaceous grains in carbonaceous meteorites also exhibit Raman spectroscopic features similar to those of figure 3-7. These grains are also the bearers of isotopic ratios of D/H that approach those ratios observed in interstellar molecules.

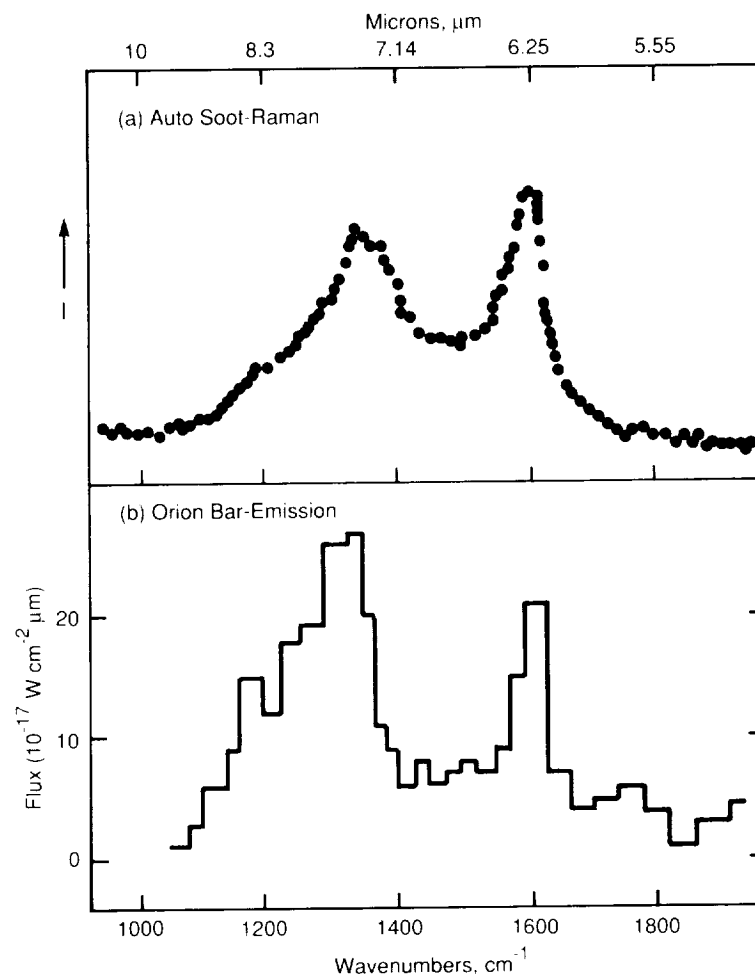


Figure 3-7. Comparison of the Raman spectrum of auto soot, a collection of polycyclic aromatic molecules, with the 5- to 10-micrometer emission features in the Orion bar.

The composition of interstellar grains is a most important question for exobiology. Infrared telescopes in Earth orbit can make an important contribution to answering this question. It is important to obtain spectra covering the full wavelength scale from 2 to about 20 μm to identify as many characteristic groups as possible. Because the 5- to 8- μm region of the spectrum, containing, for example, the important C-C stretches and C-H bending modes, is blocked from the ground, infrared observations from Earth orbit (ISO and SIRTf) are required. These satellites have the added advantage of the reduced thermal background of a cooled telescope. Thus, even in the 10- μm atmospheric window, they can make an important contribution because much fainter sources can be observed than from the ground.

Among the questions that have to be addressed are, "What is the composition of molecular grain mantles accreted inside molecular clouds?" and "Are photolyzed grain mantles an important component of the interstellar dust?" Carbon dioxide is one of many molecules that cannot be observed from the ground. Theoretical calculations have suggested that CO_2 may be the dominant constituent of accreted grain mantles under certain physical conditions. Absorption by atmospheric CO_2 makes detection of interstellar CO_2 impossible, even from airplane altitudes. Ultraviolet photolysis will produce complex molecules that cannot be formed by grain-surface reactions. Detection of such molecules will help unravel the photochemistry taking place. Specifically, the determination of the relative abundance of aromatic to aliphatic species is very important. The former may be related to dust formed in stars (e.g., small condensed carbonaceous grains), while the latter may be produced by photolysis. High-resolution spectra in the 3.2- to 3.5- μm region could answer this question. The C-H stretching modes are weak compared to the continuum dust extinction. Because there is significant atmospheric CH_4 absorption even at a good site (such as Mauna Kea), cooled space infrared telescopes are needed. Faint sources with long path lengths through the diffuse interstellar medium can then be studied.

Infrared observation can also be used to study the formation sites of interstellar grains. One particularly important question is, of course, "Do carbonaceous or other biogenic-element-bearing grains condense in the outflow from novae and supernovae?" and if so, "What is their precise composition?" The tentative identification of infrared fluorescence from PAHs around planetary nebulae is particularly interesting. These species, which are presumably the molecular precursors of carbon grains, have obviously been formed only recently in these objects.

High-resolution studies of the 7.7- μm band in a variety of sources could reveal profile variations related to differences in the collection of PAHs. Correlation studies among the different infrared emission bands are also important in this respect and could produce insight into the actual synthetic route. As yet undiscovered infrared emission features may be present in wavelength regions that are not observable from airplane altitudes. Searches for the emission features in

absorption against background stars with diffuse interstellar medium material along the line of sight is important to assess the possibility of the ubiquitous presence of PAHs in the diffuse interstellar medium. Such absorption studies of the outflow from carbon-rich, late-type giants could elucidate their formation process.

Important progress in the study of interstellar dust can also be expected from visible and ultraviolet studies. In particular, ultraviolet extinction and polarization studies of stars behind dark clouds represent a largely unexplored area, and with both HST and ASTRO it will be possible to make such studies and derive average grain sizes for such regions. This could answer the important question, "Do interstellar grains coagulate into fluffy aggregates inside molecular clouds or does grain growth mainly take place through grain mantle formation?" It may also be possible to study how the composition of the grain surface influences the rate of grain growth. The HST could also search for structure in the ultraviolet extinction curve, similar to the diffuse interstellar bands in the visible. Optical and ultraviolet spectroscopy with HST of high-velocity shocks (100–200 km/sec) can yield the elemental abundances in the post-shock gas and provide insight into the destruction of interstellar grains. Finally, with the ASTRO satellite, it will perhaps be possible to study the dust extinction curve toward nearby stars for wavelengths shorter than the Lyman limit. Presently no information of this sort is available. Many materials have electronic transitions in this wavelength region that may show up as prominent extinction bumps for small particles.

The observational projects outlined here require much laboratory and theoretical effort. Studies of the condensation process in the outflow from late-type giants, planetary nebulae, novae, and supernovae have to be undertaken. In particular, the role of large aromatic molecules in the formation of interstellar carbon grains should be investigated and their physical and chemical properties determined in the laboratory. Laboratory spectra of candidate materials have to be measured for a successful interpretation of interstellar spectra. Laboratory studies are a prerequisite for our understanding of the role of grain-mantle photolysis in the interstellar medium. Such studies may also provide insights into the interchange of molecules between the gas phase and the solid phase in molecular clouds.

Suggestions for Further Reading

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3.11 Evolution of Elemental Abundances in Galaxies

The biogenic elements available for the formation of planets, and perhaps life, in external galaxies must be measured in order to estimate the probability for planetary and life formation. To have an exobiological impact, these elements must be present in the interstellar medium rather than locked up in stars. There, they can be in either gaseous or solid form; measurements are needed of both states in order to estimate the total abundances available for planetary formation. Furthermore, elemental abundance gradients within a galaxy will determine where planets having the “necessary” inventory of biogenic elements are most likely to form. Thus, measurements should be made of galaxies of different ages and morphological types so that the production rate of biogenic elements in the universe as a whole can be accurately estimated. Is it possible that there are galaxies that have not yet attained the stage of nucleosynthetic evolution necessary to provide the raw materials from which geologically active planets can be produced?

Observations of the biogenic elements in the gas phase can be made only spectroscopically, primarily in the ultraviolet, visible, and infrared spectral regions for atoms and in the infrared, submillimeter, and microwave regions for molecules formed from the biogenic elements. Spectral resolutions of $\lambda/\Delta\lambda \sim 1000$ are needed to clearly separate the spectral lines from the background continuum. Even higher spectral resolutions allow studies of the velocity distributions within the lines, reducing the spatial resolution penalty incurred by studying objects as distant as external galaxies. For evaluating Earth-orbiting observatories, we split the observations into separate spectral regimes.

Ultraviolet or visible lines must be seen either by emission from, or in absorption against, a high-temperature gaseous environment such as a stellar photosphere or an HII region. Studies of heavy-element (carbon, nitrogen, oxygen, etc.) abundances inside stellar atmospheres are important, since the elements can be returned to the interstellar medium in the course of stellar evolution, making them available for incorporation into subsequent generations of stars and planets. Outside stellar atmospheres the material in interstellar space will generate absorption features in the ultraviolet and visible regions. These features can be strong in comparison to features at longer wavelengths because the oscillator strengths are greater at the higher frequencies. Thus ultraviolet/visible spectroscopic observations are very sensitive to trace amounts of biogenic elements in the diffuse interstellar medium. However, as will be noted later, these observations must be complemented by longer-wavelength measurements of the dense molecular cloud regions. Studies of emission lines from extragalactic HII regions will also be useful in surveying heavy-element abundances, although the infrared fine-structure line observations (see below) require less correction for extinction.

Infrared observations of biogenic elements in the gas phase are necessary to complement the shorter-wavelength observations. Abundances derived solely

from the shorter-wavelength studies will be too low, in general, since the dense clouds, where many of the interstellar heavy elements reside, are impenetrable to visible or ultraviolet light. However, these regions are transparent to longer-wavelength radiation; thus smaller extinction corrections are necessary in the infrared. Infrared line radiation can be used to measure the abundances in both neutral and ionized regions. The lines of interest have wavelengths ranging from 4 to 200 μm , with the different lines being sensitive to different excitation temperatures and densities. Some of the more important lines include the 157- μm C^+ line in neutral regions as well as the OIII lines at 88 and 52 μm and the NeIII line at 16 μm in the ionized regions.

The rotational transitions of many of the molecules containing biogenic elements lie in the microwave region of the electromagnetic spectrum. Observations at these wavelengths will complete the biogenic element surveys by probing the very densest and coldest molecular clouds.

Measurements of the biogenic elements residing in the dust component of external galaxies require different instruments and observing approaches than do gas-phase studies. The dust itself can be seen either in absorption in the ultraviolet through near-infrared or in emission at longer wavelengths. High-resolution spectrometers are not advantageous in determining the dust composition, since the solid-phase absorption features are broad in comparison with the gas-phase features. Resolving powers of $\lambda/\Delta\lambda \sim 100$ or less are best since they are sensitive. The total quantity of dust in galaxies is best measured through broad-band infrared photometry; telescopes with cooled optics are desirable because of their high inherent sensitivity.

The planned Earth-orbiting space observatories (Appendix B) will be of tremendous utility in measuring biogenic element abundances in other galaxies. The elimination of atmospheric effects will increase sensitivity so that objects, which from the ground can be studied only in the Milky Way, will be routinely observed in nearby galaxies. The sensitivity gain will also allow detailed studies of even more distant objects for the first time, so that cosmological evolution effects on the availability of biogenic elements can be studied.

The three major observatory-class orbiting telescopes—HST, SIRTf, and LDR—will be the most useful of all the planned astronomical spacecraft since they alone have the fine angular resolution and pointing ability needed to work on extragalactic objects.

For ultraviolet, visible, and near-infrared studies, the HST will be the most useful observing platform. The advertised angular resolution of better than 0.1 arcsec is sufficient to study individual stars in selected regions of nearby galaxies such as M31. In addition, the first generation of science instruments includes two spectrometers operating between 1150 and 8000 Å with resolving powers ranging from $\lambda/\Delta\lambda = 10^2$ to 10^5 . This is more than adequate for visible gas-phase elemental abundance studies in external galaxies.

For wavelengths from 2.5 to 100 μm SIRTf is the most sensitive telescope now planned for Earth orbit. At very high spectral resolutions ($\lambda/\Delta\lambda \gg 10^3$), HST (with a possible second-generation infrared spectrometer) and LDR will have an advantage at wavelengths less than 2.5 μm and longer than 100 μm , respectively, because of their larger collecting areas. At very high resolving powers, this advantage overtakes the cooled-optics advantage of SIRTf. There is an infrared spectrometer proposed for SIRTf that is planned to operate between 2.5 and 200 μm with two resolution modes of $\lambda/\Delta\lambda = 50$ and 1000. The high-resolution mode is adequate for extragalactic studies of the strongest infrared fine structure lines; for example, it will be capable of measuring the very important 157- μm CII line out to a redshift of $z = 0.3$. The sensitivity of the SIRTf infrared spectrometer is expected to be high enough that observations can easily be made of other infrared lines required to trace the biogenic elements encased within dense molecular clouds in either neutral or ionized states in normal galaxies out to distances of 500 Mpc. This distance encompasses a very large number of galaxies, enough that biogenic elemental abundance studies can be correlated with other factors, such as galactic morphological type.

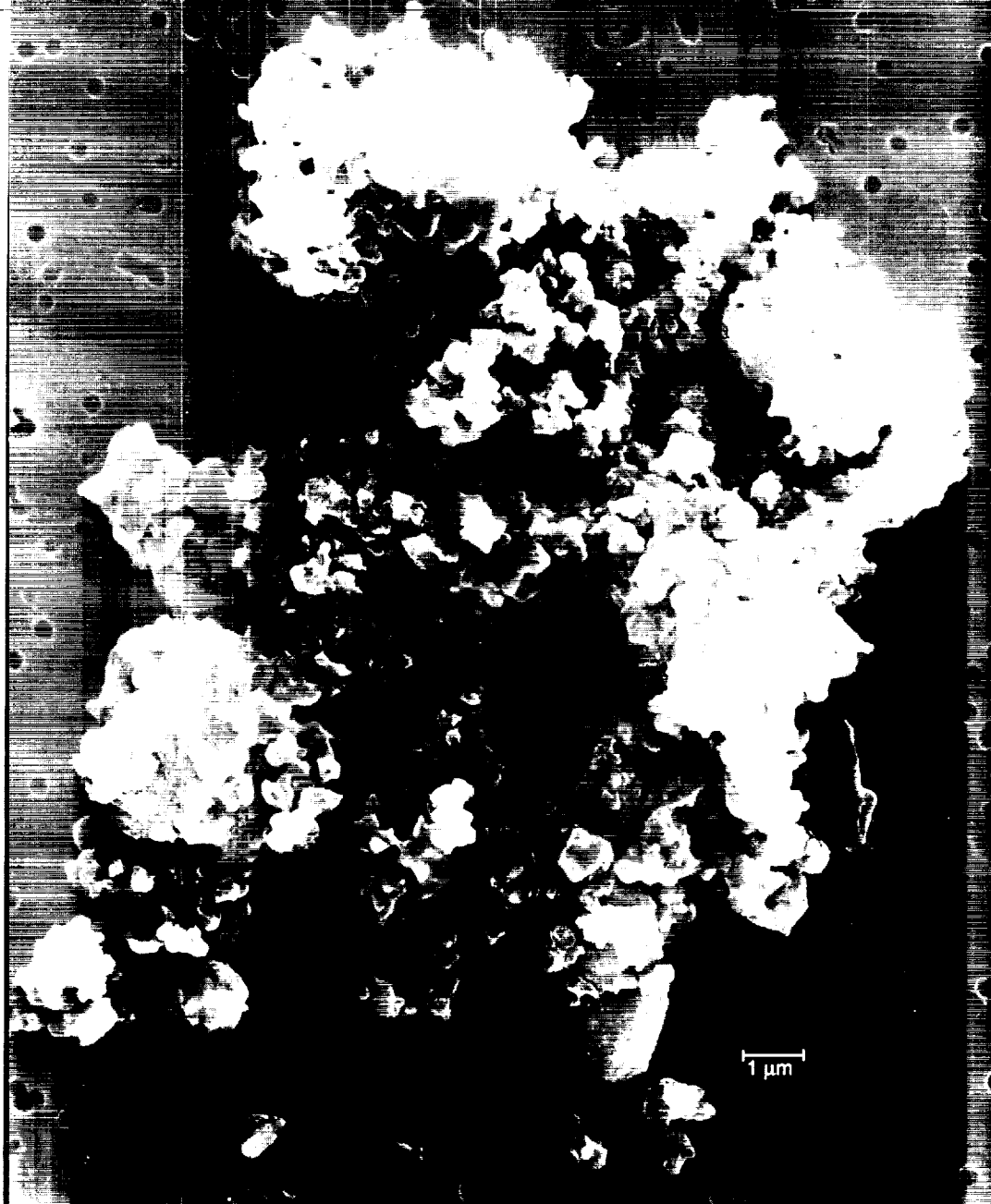
There are two infrared spectrometers of high enough resolution for infrared fine-structure line observations listed in the strawman instrument complement of LDR. The large aperture of this telescope will allow good angular resolution for abundance gradient observations of the biogenic elements and the large collecting area will make it unequalled for submillimeter line measurements.

Of all the planned Earth-orbiting telescopes, SIRTf is the best suited for carrying out dust studies in other galaxies. The cold optics of this telescope will allow for very high sensitivities. For example, the planned infrared photometer will be capable of measuring the integrated mass of dust in normal spiral galaxies out to red shifts of $z = 2$. The composition of the dust can be determined using the planned SIRTf infrared spectrometer, which has a low-resolution mode that was developed for detecting dust features in galaxies with large red shifts. In the low resolving power mode of $\lambda/\Delta\lambda = 50$, the SIRTf spectrometer sensitivity is limited only by the background emission from the zodiacal dust. This high sensitivity would allow observations of the 10- μm silicate dust feature in spiral galaxies out to a red shift of $z = 1.5$. While the warm optics of the LDR make it less sensitive for observations of the most distant and faint extragalactic objects, its larger aperture will allow studies of the distribution of dust in nearby galaxies with 20 times the angular resolution of SIRTf.

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ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Chapter IV

Cosmic Dust Collection

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and J. Wolfe

Primitive solar system objects such as asteroids and comets occupy an important place in exobiology because their contents include water, organic matter, and minerals that, together, are considered prerequisites for the prebiotic evolution of biological materials from chemical systems. In addition, these materials are samples of planetesimals that contributed some fraction of the volatile contents of the terrestrial planets. They also contain abiotic organic compounds and carbonaceous materials that may be attributed to origins in the parent bodies, the solar nebula, and galactic environments that preceded the nebula. Therefore, their origins and the origins of their components have a bearing on understanding the cosmic evolution of biogenic compounds and the development of models for prebiotic evolution on planets. To asteroids and comets, however, should be added a third category of materials of exobiological interest, "cosmic dust," the information about the content of which shows promise of supplementing and complementing that of the first two types of material.

The designation cosmic dust is applied to extraterrestrial particles less than 1 millimeter in diameter. Some of these particles that have entered Earth's atmosphere have been collected by high-flying aircraft. It is believed that most are debris from comets and asteroids that predate our planetary system and may have thus originated outside the solar system. Isotopic anomalies in primitive carbonaceous meteorites suggest that dust originating from their cometary or asteroidal parent bodies contains components formed in the presolar epoch. In any case, cosmic dust should be viewed as possible samples of primordial material that have been preserved since the early history of the solar system. In the exobiological context, laboratory studies of the biogenic elements and compounds in these minute objects will open windows through which physical and chemical processes operating in the galaxy or early solar system may be

Scanning Electron Micrograph of a porous chondritic micrometeorite collected in the stratosphere by a NASA Ames U-2 aircraft.

discerned, as has been the case with meteorites. Through such windows it may be possible, in ways not available with meteorites, to elucidate the pathways taken by biogenic materials from their origins in stars to their incorporation in some of the earliest objects formed in the solar system.

Meteorites found on the surface of the Earth have been the traditional source of primordial extraterrestrial materials, and they have been, and will continue to be, valuable windows into the past. However, there are two major limitations with this source of samples. One is that the stress of atmospheric entry prevents structurally weak materials from surviving in pieces as large as conventional meteorites. This exclusion effect prevents typical cometary matter from surviving as recoverable macroscopic samples. Studies of the fragmentation of meteors in cometary meteor showers have shown that typical cometary material is more than an order of magnitude weaker than the most friable of the recovered meteorites. The second limitation with meteorites is that, with the exception of the lunar meteorites, it has not been possible to associate collected samples with their sources. It is widely believed that conventional meteorites are fragments of asteroids, but it is not possible to prove this or to identify the specific parent bodies of recovered samples. There are many distinct families of meteorites, and it is unfortunate that their measured chronologies and detailed physical and chemical properties cannot be associated with specific bodies or locations within the solar system.

An approach for overcoming the problems of the atmospheric exclusion effect and the unknown origin of meteoritic samples is to collect meteoroids directly in space. From Earth orbit this is not practical for meteoroids as large as conventional meteorites because the flux is too low, but it is possible to collect the much more abundant submillimeter particles, cosmic dust. The flux of 0.1-mm particles is $1 \text{ m}^{-2} \text{ yr}^{-1}$ and that of 0.01-mm particles is $1 \text{ m}^{-2} \text{ day}^{-1}$. With large areas and long exposure, it should be possible to collect a few particles of millimeter size and large numbers of smaller samples. Dust-collection experiments in space began during the Mercury program, but progress was slow, partly because of limitations on the size and exposure times of collectors that could be exposed and then returned to the laboratory. This situation changed dramatically in April 1984 with the launch of the LDEF. Opportunities for long exposures with Earth return will be common in the future, and it is likely that considerable progress can be made in the meteoroid collection field.

4.1 State of Knowledge

The most detailed information on the properties of individual interplanetary dust grains has come from laboratory studies of 5- to 50- μm particles that have been collected in the stratosphere with U2 aircraft. The extraterrestrial nature of the samples has been proven by detection of trapped solar wind particles and tracks of solar cosmic rays, unique indicators of exposure to space.

A variety of particle types have been identified, but the most common are particles that have chondritic (solar) abundances for all the major and minor elements found in meteorites. They are black, contain 2- to 5-wt% carbon, and have elemental compositions identical to CI and CM carbonaceous chondrites. Among the chondritic composition particles there are two clear subdivisions: those that contain hydrated minerals and those that are anhydrous. The hydrated particles are often rather compact and the bulk of their mass is contained in clay minerals. In some cases the abundant hydrated phases are serpentine minerals that closely resemble those in CI/CM chondrites. However, in other particles the hydrated minerals are distinct from those common in carbonaceous meteorites and they also contain minor anhydrous phases, such as low Ni-pentlandite, that have not been identified in meteorites. Some of the hydrated cosmic dust particles may be samples of the same parent bodies that produce the CI and CM meteorites, but others in this class are mineralogically distinct and probably did not come from the CI/CM parent bodies. The anhydrous particles are unique and are unlike any established meteorite type. They are the only known case of a carbon-rich chondritic composition material that is composed entirely of anhydrous phases. These particles are often exceedingly porous and are similar in strength to the fragile materials that are observed as cometary meteors. The pore spaces in the particles may have originally been filled with ice. The anhydrous particles are aggregates of grains ranging in size from ~ 50 Å to micrometers. Some grains are single minerals (enstatite, olivine, iron sulfide, or carbides), but others are themselves microaggregates of very tiny crystals embedded in carbonaceous material. Carbon occurs as binding material for the grains, as discrete amorphous clumps, and as coatings. Isotopic analysis of hydrogen associated with carbon in the particles has shown D/H enhancements as high as a factor of 10 relative to solar. The bulk D/H enhancement is higher than that found in most meteorites. High D/H fractionation in interstellar environments is usually attributed to ion-molecule reactions.

4.2 Science Questions

The primary goals of future dust-collection experiments in Earth orbit are to collect materials that cannot be recovered as conventional meteorites and to directly associate this material with specific comets, with specific parent bodies (particular asteroids), or with interstellar origins. The samples should then be returned to Earth for detailed elemental, isotopic, molecular, mineralogic, and structural study, with exobiological interest focusing on the nature and abundances of the biogenic elements (carbon, hydrogen, nitrogen, oxygen, sulfur, phosphorus) and their compounds. The particles obtained would always be small, and depending on the collection technique, they would be at least somewhat altered during acquisition. Even if the particles could not be collected in pristine condition from Earth orbit, they could at least be collected in a form that would give accurate elemental and isotopic compositions for grains over a large size range.

The collected dust samples can play a unique and important role in the future study of primitive solar system materials. Probably the most significant aspect of this effort would be the collection of materials from a variety of specific comets and the capture of interstellar dust in transit through the solar system. The laboratory analysis of both cometary and interstellar particles would provide the first direct information on cometary and interstellar grains. It is particularly intriguing that it might be possible to examine the abundances and possible forms of the biogenic elements and compounds in materials that existed before and just after the formation of the solar system. In addition, elements heavier than oxygen in the interstellar medium occur primarily in the form of interstellar grains, and contemporary grains are probably very similar to those that contained most of the condensable elements in the solar nebula during its collapse stage. Dust particles in comets are believed to be well preserved grains that may have been typical of the materials that existed at the outer fringes of the solar nebula. The collection of dust may then provide direct information on the composition of some of the original material from which the solar system formed, and the composition of collected grains can then provide useful data for modeling solar nebula processes and environments.

Among the important scientific questions pertinent to exobiology that could be addressed by detailed laboratory studies of cosmic dust are the following:

1. What similarities exist in the relative abundances of the biogenic elements and compounds in interstellar, cometary, and meteoritic samples? Can these similarities be traced to common sources and histories in the interstellar medium, the solar nebula, or the parent objects?
2. What connections exist between the gas-phase chemistry observed in interstellar clouds and the organic chemistry of cometary and interstellar dust?
3. What evidence of grain-mediated organic chemistry in interstellar clouds can be found in interstellar or cometary dust?
4. What role has water played in the chemistry and mineralogy of interstellar dust particles? Do they contain hydrous silicates?
5. What evidence is there for the influence of liquid water on the chemistry and mineralogy of cometary samples?
6. What materials in interstellar and cometary dust can be attributed to discrete nucleosynthetic sources? Are they the same as can be inferred from some components of meteorites?
7. What correlations can be drawn between astronomical observations of interstellar clouds and the structure and compositions of collected cometary and interstellar dust?
8. Did radiation-induced polymerization of organics occur in presolar or early solar system environments?

A special attraction of the dust-collection approach is the abundance of dust particles, providing the capability to collect samples from a variety of comets and thus address the possible diversity among comets. The properties of come-

tary bodies may differ because of conditions and processes that existed at the time and location of their origin, or they may differ because of endogenic alteration processes such as might occur from heating caused by ^{26}Al decay. The capability of evaluating diversity among comets is a unique attribute of the dust-collection approach.

A major goal of solar system research is the direct return of a pristine cometary sample collected from a dedicated mission to a comet nucleus. However, even when such advanced missions occur, they will be limited by cost to a small number of bodies and will not adequately study the diversity question which can be addressed by cosmic dust collection. The dust collection may also provide new insights into existing meteorites by providing criteria for identifying possible cometary or presolar materials in existing collections of meteorites and interplanetary dust. For example, the recent identification of meteorites from the Moon was possible only because analyses of lunar samples had defined several characteristic properties of lunar material. It is assumed that appropriate analysis of meteorites and interplanetary dust particles collected via U2 aircraft will continue and that collections can be made in low Earth orbit, but in addition it would be highly desirable to sample directly the source regions of the interplanetary dust population. Those sources are comets and asteroids, with the former believed to be by far the dominant source. Sample-return missions to comets are currently under consideration and, although that topic is strictly outside the scope of this report, its relevance and potential value to the Earth orbital investigations justify reiteration of the importance of such a mission.

Finally, a conceivable but remote possibility concerns the issue of panspermia. If extraterrestrial microbes have been dispersed in space and make a real contribution to the cosmic-dust population, they may be included in any collected samples. Routine microscopic surveys of the collected particles could be followed up by detailed nondestructive chemical analyses. In the event that a number of putative microbes were detected, attempts at culturing them for viability and reproduction could be considered. Because of contamination and collection problems in space, it is probably best to conduct panspermia experiments in the stratosphere where large numbers of particles can be obtained with minimal contamination. Samples could be cultured directly on the collection substrate and correlation of growth with an actual extraterrestrial particle would be evidence for capture of an organism.

4.3 Technical Approach

The proposed new dust-collection experiments will require both particle collection and measurement of orbital parameters. The trajectory and speed of an incoming particle must be measured with sufficient precision so that a good match can be made between the collected particle and the source body. The orbits of dust particles evolve because of Poynting-Robertson drag, which decreases the eccentricity and semimajor axis with time, but does not alter the

inclination. Most particles probably will not have uniquely determinable parents and will be sporadic. A small fraction of the detected particles will have not yet had their orbits significantly modified and it will be possible to match them with their source body. Because it may be possible to detect large numbers of particles, the total number of particles with identified sources could, in principle, be large. Orbital evolution caused by Poynting-Robertson drag is slowest for the larger particles and so the best collection experiment is one that collects large numbers of relatively large dust particles. The science return from laboratory analysis is also greater for large particles.

The most straightforward technique for determining the orbital elements of an impacting dust particle is to measure the time of flight (TOF) and path direction of a particle that first penetrates a thin, front film, passes through an open space, and then enters a rear-collection substrate or device. This basic technique for orbit measurement was actually first used on Pioneers 8 and 9 over 15 years ago. The detection of the front-film penetration can be made from the light, shock wave, or ion pulse generated during the impact. The velocity (TOF) and direction measurements can be made solely by electronic methods or by a combination of real-time electronic measurement followed by later measurements of the impact sites in the laboratory. The TOF between the front film and substrate must be established electronically at the time of collection and must have a precision of a few percent. The path direction can be determined by position-sensitive detectors similar to those used for two-dimensional ionizing radiation detectors. The acoustic, light, or ion pulse can be detected by a sensor-array grid square. The path direction requires the measurement of the location of the front-film penetration and entry into the rear substrate. A modification of the purely electronic approach is to use coarse position sensors to identify the general region where the impact occurred and to precisely measure the TOF. After return to the laboratory, the penetration hole and rear impact can be located and measured to determine the particle path to great precision.

Dust collection from Earth orbit is complicated by the high velocity of the incoming particles. Impact velocities range from 4 to over 70 km/sec and the typical impact velocity for 10- μ m particles is about 15 km/sec. Even at the minimum velocity, the kinetic energy exceeds the binding energy, and non-destructive collection is by no means a trivial process. The most developed collection concepts involve direct impact and collection by totally mechanical processes. Material was collected with some of these techniques on Gemini, Skylab, and Solar Max, and there is considerable expectation that the large number of similar collection experiments on LDEF will also return important data. Although the direct-impact techniques can recover some unmelted material, in general the collection is destructive and most structural information is lost. True nondestructive collection would require a device that could decelerate incoming particles without causing excessive heating or mechanical stress. Low-pressure gas cells, foams, and electrostatic or electromagnetic devices have been

suggested as possible approaches for this type of collection, but they are only in early stages of development.

An example of an impact collection technique is the capture cell in which a particle penetrates a thin film and enters an enclosed volume where vapor and debris are trapped. For capture cells the information that is obtained for a particle is bulk elemental and isotopic composition, as well as some limited data on shape and density from the shape and size of the penetration hole. The compartmentalization of capture cells allows the collection of discrete particles over a wide size range. A major advantage of capture cells is that all condensable materials are trapped in the cell for later analysis. Other destructive collection schemes involve direct cratering into either a solid or a porous material. For impacts at moderate velocity into some metals, the efficiency of retention of meteoroid residue as material lining the crater bottom can be appreciable. This technique has the advantage that the sample is highly concentrated and is not diluted with collection material, as is the case with capture cells. Disadvantages are that volatile materials are lost preferentially and at the higher velocities all the projectile is vaporized. The shock-loading of the impacting particle can be considerably decreased by using a low-density substrate material. This can be a foam, a stack of thin foils, or a suspension of particles or fibers. If the velocity is not extreme, particles can be collected intact with this approach in the sense that some original phase and structural information is preserved. It is unlikely that fragile particles can be captured in pristine condition, but it is likely that particles or components of particles that are strong mineral grains can be decelerated without melting or severe heating. Recent work with impacts recovered from Solar Max have demonstrated that some fragments of fragile particles can be captured in unmelted form.

There are two generic approaches to "nondestructive capture" of hypervelocity particles: passive capture and active capture. The passive approach uses input into suitable low-density, inert capture media to absorb kinetic energy in a manner that minimizes alteration of the particle. Active collection utilizes force fields to decelerate particles.

The success of passive intact capture of hypervelocity particles rests on the ability to absorb the maximum amount of particle kinetic energy by a passive capturing medium while maintaining the energy removal rate below the threshold that will cause particle damage. Examples of possible passive capture media are low-density polymeric foams, suspended micrograins, gas, void-metal composites, felts, and aerogels. Considerable laboratory success has been realized from the use of low-density polymeric foams to capture comet analog silicate grains in an organic binder at speeds up to 6 km/sec. Laboratory tests with pure aluminum projectiles have demonstrated recovery of 60% of the projectile mass at speeds of 7.9 km/sec.

A considerable body of laboratory data suggests that the passive capture techniques can be used to collect meteoroids in space. It is likely that both mineral

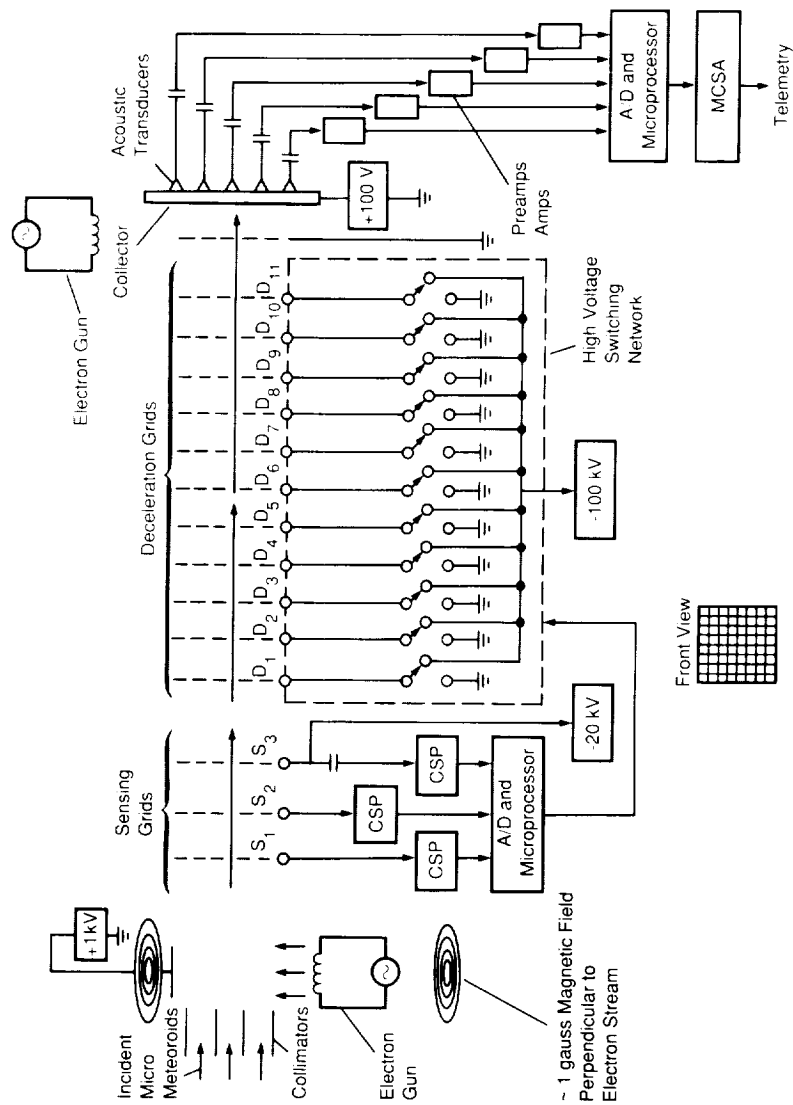


Figure 4-1. Conceptual design of an electrostatic cosmic dust collector.

grains and organic materials can be collected in relatively unmodified form. Strong, low-velocity particles can be captured intact. The fragile particles that may be characteristic of comets will probably fragment during collection, but even for the most fragile materials it is expected that individual solid components will be recovered without major modification. The passive technique is relatively well developed and could be used at the present time.

Totally nondestructive collection is theoretically possible using electrostatic or magnetic fields to decelerate micrometer-sized meteoroids from cosmic velocities. Figure 4-1 shows a conceptual design of an electrostatic collector. Particles are charged with an electron beam and then decelerated by electrostatic fields that retard the particle motion. This is essentially the inverse of electrostatic dust accelerators used in the laboratory to calibrate micrometeoroid impact sensors such as those used on the flybys of comet Halley. In the laboratory, micrometer and submicrometer particles are highly charged and then accelerated with a potential of a few million volts to attain velocities as high as 50 km/sec.

Feasibility studies are currently under way to determine whether the electrostatic technique can be used for practical and efficient collection in space. Although there have been conceptual studies, there is no laboratory experience with actual capture of hypervelocity particles. The active capture approach has many attractions, but there are formidable problems that must be solved before a significant number of particles in the nanogram to microgram range can be collected.

4.4 Technology Needs

Only a few meteoroids have been collected in space and, although orbital measurements have been made for particles, they were not made for collected material. Presently there is a considerable amount of activity in the collection and detection fields. An impressive set of particle impact detectors flew on the comet Halley probes, Giotto and Vega, and are planned for the Jupiter probe, Galileo. Particle collection experiments involving capture cells and cratering into solids are carried on LDEF and the Soviet space station. The technology of hypervelocity capture of small meteoroids is also under development for possible use on a comet-sample-return mission using a flyby spacecraft on an Earth-return trajectory. This mission is part of the Solar System Exploration Committee (SSEC) core program. There is progress being made in the collection and the detection of particles, and it is timely to combine the technologies to produce a device that collects particles and measures their orbital parameters. The major technology needs are to refine the collection techniques and to adapt detection methods so that precise speeds and impact directions can be measured.

The capture techniques need to be refined so that some intact particles can be collected, and volatile elements such as carbon, nitrogen, and hydrogen will

not be lost to analyses. For example, capture cells made of "getter" materials have been discussed wherein the meteoroid vaporizes enough getter material to trap reactive elements. The specific needs in the passive collection area are to develop efficient materials or devices that trap meteoroids or their debris without causing significant chemical or physical alteration or contamination with collector or spacecraft materials. Some of this development can be done on the ground using particles accelerated to high velocity with light gas guns, plasma drag accelerators, or electrostatic accelerators. The ultimate tests must be made in Earth orbit with real meteoroids. Extensive development will require frequent exposure opportunities.

The detection technology needs to be adapted to the particular problem of accurately measuring orbital parameters of micrometer- to millimeter-sized particles. The required accuracy of the velocity vector is about a few percent. Plasma pulse detectors were used for TOF and impact-angle measurements on Pioneers 8 and 9 and the LEAM (lunar ejecta and meteorites) instrument placed on the lunar surface by Apollo 17 astronauts. Improvements in the plasma area would be to simplify the technique so that large areas could be instrumented at minimal cost. Another position-sensitive technique that is being actively studied involves piezoelectric sensors that use arrival times in a detector array to pinpoint the exact impact location. A final technique uses a polarized PVDF plastic film that generates electric pulses when it is perforated. This material needs no electrical bias. The impact point is measured by signal-delay times. It appears that there are several detector technologies that are suitable for orbital parameter measurement and the major task is probably to develop a workable system combined with the collection capability.

4.5 Opportunities

In the near term, collection experiments can use collection areas approximately a meter squared and exposure times of months. Much larger areas and exposure times would be desirable to collect very large or very rare particles.

Near-term exposure and recovery opportunities include recoverable satellites such as LDEF and EURECA. A first-rate collection and trajectory measurement experiment of several square meters' area could be included on an Explorer-class mission, with subsequent sample recovery and return to Earth. This could be a dedicated mission or an add-on to a multiinstrumented spacecraft. A timely completion of such a mission would be of considerable value in planning larger and more complex collectors for the Space Station. The Shuttle itself does not have sufficient exposure times to be useful except for simple tests involving a few impacts. A 2-m² collector exposed for a year would provide an excellent opportunity to collect a significant number of 0.01- to 0.1-mm particles. A 100-m² collector on Space Station would provide the unique opportunity to collect millimeter-sized particles. Because the reason for having a large area is

the collection of rare particles, only cells that were impacted would have to be recovered. Once set into operation, the collector would require very little attention. Perhaps twice a year cells that received major hits would be recovered for Earth return. The scientific reward for operating a large area collector would be the collection of the actual particles that produce the annual showers of cometary meteors. The larger particles collected would have become radar or faint optical meteors had they been allowed to reach the atmosphere.

4.6 Conclusions

The analysis of recovered samples of primitive solar system material provides fundamental insights into the materials and processes that existed in the early history of the solar system and thus into the cosmic evolution of the biogenic elements and compounds. With the improving capabilities to conduct ambitious experiments in Earth orbit, it now seems possible to collect small meteoroid samples (extraterrestrial dust) that can be associated with their parent sources on the basis of common orbital parameters. The major scientific advance that could come from such an endeavor would be the collection of samples that could be confidently identified as originating from the interstellar medium or from specific comets. Even though, for some experiments, particles may be significantly altered during capture, it is believed that at least their elemental and isotopic compositions can be accurately measured in the laboratory. The ultimate challenge will involve the development of a device for use on the Space Station that will collect cosmic dust without significant concomitant alteration of its chemical and physical properties.

Suggestions for Further Reading

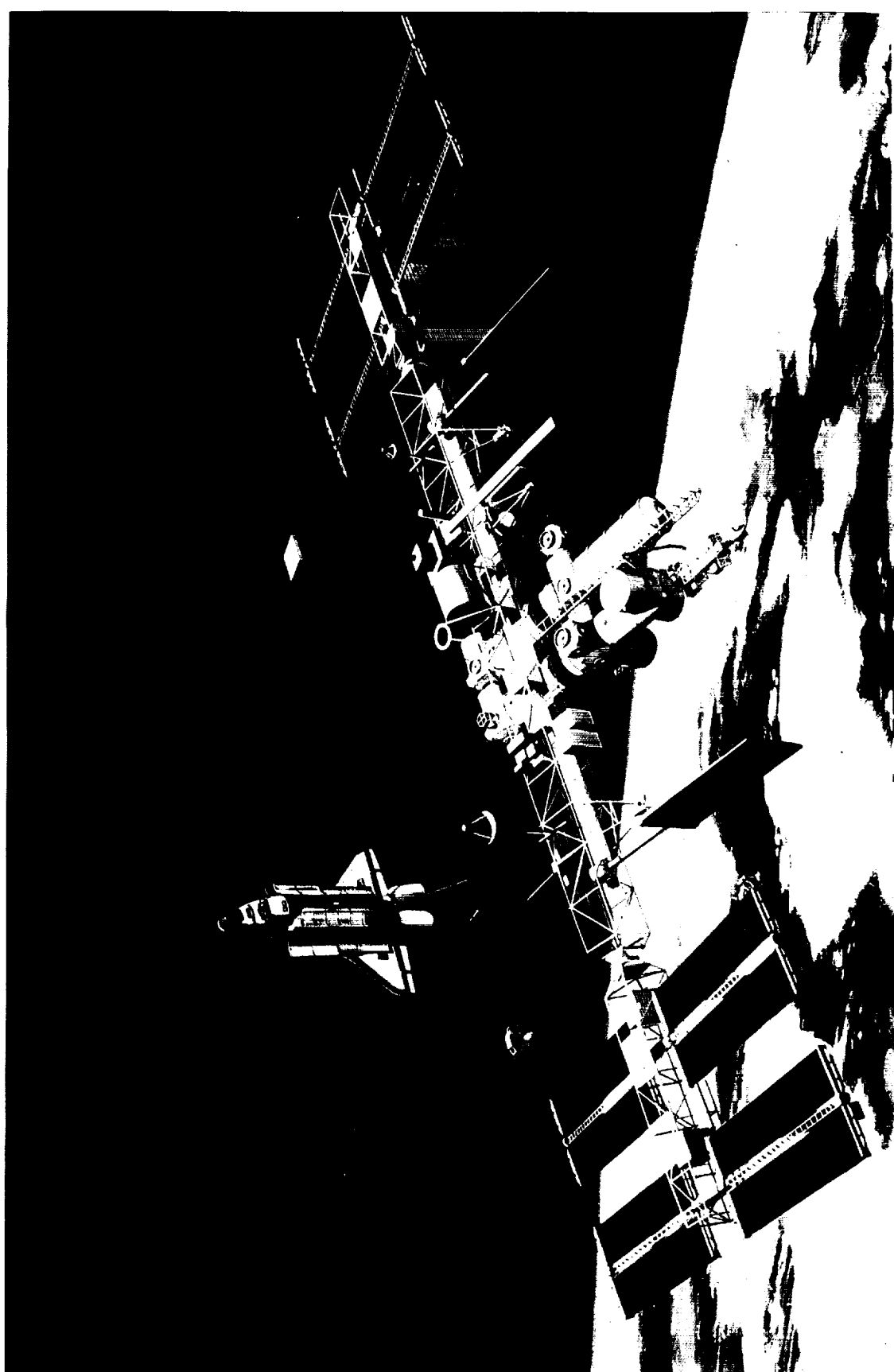
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Chapter V

In Situ Investigations

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A spacecraft in Earth orbit provides a uniquely useful environment for studies that are of central importance to modern exobiology. Such a space platform makes available special conditions including microgravity, a reasonably good vacuum with a very high pumping speed, a continuous source of high-energy neutral atomic oxygen, and a solar flux that is less attenuated than that at the Earth's surface.

In this Chapter we discuss four different types of experiments that can be performed on a space platform. These are the study of suspended grains, reactions of neutral atomic oxygen, studies of an artificial comet, and possible experimental tests of the viability of microorganisms in space.

5.1 Models of Interstellar Grains

Interactions between a gas phase and a solid phase are well known and include sorption phenomena, heterogeneous catalysis, and many other familiar terrestrial physical-chemical processes. Such interactions are also important in the space environment, particularly for the roles they play in the cosmic history of the biogenic elements and compounds. Elucidation of this history involves tracing the physical and chemical pathways taken by the biogenic elements and compounds from their origin in stars to their incorporation into preplanetary bodies, measuring the biogenic elements and compounds in the galaxy and solar system to develop theories about the formation of the solar system, and determining how the physical and chemical properties of the biogenic elements and compounds influenced the formation of the solar system and the bodies within it. In this context, interactions among gases and grains in space are

Artist's concept of a laboratory module for the Space Station.

fundamental to theories of the origins of the constituents of interstellar clouds, comets, meteorites, interplanetary dust, and all of the bodies in the solar system. Experiments capable of yielding insight into the nature of these processes are thus of great value in confirming or modifying various aspects of these theories.

Nucleation, condensation, and growth of carbonaceous particles must occur in the envelopes of carbon stars to yield the observed circumstellar dust and molecules. Similar processes are thought to occur under conditions as diverse as those in interstellar clouds and in the atmospheres of some of the outer planets and their satellites; observational evidence points to the presence of fine-grained dust (from less than $0.1\ \mu\text{m}$ to about $1\ \mu\text{m}$ in diameter, presumably containing varying proportions of hydrogen, carbon, nitrogen, and oxygen) in both types of environments. Although there are some theoretical discussions of the properties of dust based on remote spectrophotometric observations, the physical and chemical character of the materials remains poorly understood, as does the nature of the processes that produced them.

Although theories of grain nucleation, condensation, and dust growth are being developed, the complexities of the natural processes make them difficult to model. The few experimental studies that have been conducted were performed under conditions that do not permit scaling to relevant astrophysical environments. A common feature of the processes in all the environments mentioned above is that grains form and evolve over substantial lengths of time while suspended in a thin gas phase, largely, if not entirely, independent of other grains. This condition should influence the rate of formation, the chemistry, structure, morphology, and other characteristics of the dust. While this condition is difficult, if not impossible, to achieve in a terrestrial laboratory, it may be effectively simulated under microgravity conditions. Experiments conducted in Earth orbit would provide "space truth" for analogous experiments carried out in terrestrial laboratories or on computers. Furthermore, they would yield samples formed under well-defined conditions, the properties of which could be readily determined and compared with those of natural material either remotely sensed or obtained from meteorites, interplanetary dust, and dust returned from a comet.

Once grains are formed in the solar nebula, they must accrete to form the larger planetesimal-sized objects thought to have been the building blocks of planets. The rate and mechanism for planetesimal formation are believed to depend on the size distribution, composition, and structure of the original nebular dust. In theory, the ability of colliding grains to stick together depends largely on short-range, Van der Waals interactions, although electrostatic and ferromagnetic forces may come into play. It has been suggested that grains endowed with mantles containing organic matter and/or icy components should accrete and grow faster than others. Despite its implications for early solar system history, this suggestion has never been tested experimentally. Microgravity facilities would provide excellent opportunities for model studies of grain

accretion in the space environment. Rates of accretion could be determined as a function of the chemical composition, physical structure, and relative velocities of the grains.

For example, the effects of grain rotation on accretion are unknown. Large grains in interstellar space may be spun up nonthermally to angular speeds of 10^5 – 10^8 rev/sec. What happens when submicrometer core-mantle particles that are so rapidly spinning collide? Do they melt and stick or do they immediately tear apart? Up to what limiting rotational frequencies will they predominantly coagulate? One approach to answering this question would be to insert ice-coated iron needles about 0.1 micrometer thick into a cooled microgravity chamber, and spin them up with a high-frequency magnetic field. The chamber walls would have to be maintained at low temperatures—preferably ~ 20 K. Light scattering is an excellent method to then follow the process of aggregation by measuring both the scattered intensity at several angles and the polarization of the transmitted and the scattered light.

In addition to growing by the passive accretion of gaseous species to its surface, a dust grain can provide an active surface to catalyze reactions of species sorbed to it or it can itself be changed by chemical reactions with sorbed gases. Chemical reactions between gas and dust have been hypothesized to occur in interstellar clouds and in the solar nebula to account for the organic matter observed by radio astronomers in the clouds and by chemists in meteorites, comets, and interplanetary dust. These ideas are often expressed in terms of a Fischer-Tropsch-Type (FTT) synthesis in which the surfaces of silicate, metal, or metal oxide grains suspended in interstellar clouds or the solar nebula provide active sites for catalysis. Molecules of hydrogen, carbon monoxide, carbon dioxide, and ammonia sorbed on the sites at temperatures from 300 to 600 K may have been converted spontaneously to organic compounds and other carbonaceous phases. These products, in the case of the solar nebula, were subsequently retained on the grains and accreted into primitive planetesimals. According to the FTT synthesis scenario, interstellar molecules represent products of nebular synthesis that were ejected into the surrounding medium during dissipation of prestellar nebulae.

Recent data from analyses of organic matter in meteorites and from laboratory FTT syntheses suggest, however, that the FTT processes cannot explain all the observed molecular and isotopic characteristics of the natural products. What they can account for remains to be clearly established, and additional artificial syntheses may provide the clues, provided they are conducted under conditions that may be related to the natural processes.

All laboratory FTT reactions have been conducted at or near a total pressure of 1 atm with a bed of catalysts. Under these conditions, grains contact each other, chemical intermediates can migrate from catalyst sites on one grain to those on others, and opportunities exist for a diverse chemistry. In the nebular environment, the total pressure is 10^{-3} to 10^{-6} atm and dust is expected to com-

prise only about 1% of the mass. Under these conditions, sorbed gases and reactive intermediates produced on a grain would remain on that grain (or desorb into the gas phase where other processes would govern their fate) until the grain is accreted with others into larger objects; consequently, the composition and abundance of the products and the rates at which they could form may well be strongly constrained and different from those observed in terrestrial laboratories. Gas-grain interactions that are independent of a bulk solid phase should be amenable to study under microgravity conditions.

Other hypothetical gas-grain processes of nebular or interstellar relevance that merit study include the hydration of silicate grains to phyllosilicates by gaseous water, the photoirradiation of icy mantles of grains by starlight, and the thermal evolution of interstellar condensates in the solar nebula.

Technology is being developed on Spacelab to levitate individual small neutral particles (<1-cm-diameter) in acoustic levitation chambers. (Charged particles can be levitated electrostatically.) These levitation devices allow full control of the dynamics of the particle, including translation about the levitation chamber, spin angular momentum and orientation, and shape for liquid droplets. This technology could be used to suspend grains in gas chambers to study the physical and chemical interactions between gases and grains. The goal of such experiments would be to understand gas-grain processes in interstellar clouds and in the primordial solar nebula. An additional experiment might be to examine the collective response of a large number of small suspended particles with various initial conditions, including a central force, to simulated nebula condensation processes.

5.2 Reactions of Neutral Atomic Oxygen

The continuous source of oxygen atoms flowing with a narrow range of high velocities in low Earth orbit provides a unique opportunity to study oxygen atom chemistry as it relates to biological and biogenic molecules. The glow observed on the windward surfaces of the Space Shuttle shows that the differential velocity of about 8 km/sec between the Shuttle and ambient oxygen atoms is sufficient to overcome the activation energy for reaction between ground-state oxygen atoms and certain, as yet unspecified, large molecules at rates sufficient to permit detection. Oxygen atom reaction rates and activation energies could be studied by injecting various reactants into a cell through which the oxygen atoms flow and monitoring the products downstream by either absorption or emission spectroscopy in the ultraviolet, visible, and perhaps infrared. Impact velocity can be varied from an upper limit of 8 km/sec to a few meters per second by having the incoming stream of oxygen bounce off several deflection plates or by injecting the reactants with a velocity vector either parallel, antiparallel, or perpendicular to the incoming beam. Interesting reaction partners to choose from are plentiful with, for example, bacteria and biologically

relevant molecules forming one class, and simple molecules relevant to planetary atmospheres and interstellar chemistry forming another.

The reactions of energetic neutral oxygen atoms with large molecules is a completely unexplored field, and it is quite likely that a new area of chemistry exists. That the source of the Shuttle oxygen glow has not been determined by an extensive literature search underscores the uniqueness of a continuous source of energetic neutral oxygen atoms.

5.3 An Artificial Comet

Organic components of the gas and dust play a prominent part in many of the new and exciting results from the study of comet Halley. Foremost among these results were the discoveries of abundant, fine-grained dust composed of dark, apparently carbonaceous, matter that mantles inactive regions and is ejected from active regions of the comet surface; evidence for CO and CO₂ as parent molecules, in addition to H₂ and HCN; and CN jets associated with the emission of dust from the nucleus. Yet, unanswered questions remain regarding parent-daughter molecular relationships and the structure and composition of the dust rich in the biogenic elements. For instance: What parental species in addition to HCN are needed to explain the abundance of the CN radical? What is the role of dust in contributing to gaseous species in the coma? What properties predispose the grains to be retained as mantling material? What are parent molecules for CS, C₂, and C₃? What species are responsible for the 3.2- to 3.6- μ m emission features suggestive of C-H bonds?

Although these questions specifically address unknowns in the composition and chemical evolution of comet Halley, the answers would apply to virtually all comets. They reflect continuing uncertainties about the interstellar versus nebular origin of these objects and their constituents, their relationships to other primitive bodies in the solar system, and the contributions they may have made to prebiotic evolution and the inventories of the biogenic elements and compounds on Earth and the other terrestrial planets. The pertinence of all these issues to exobiology continue to make the study of comets an area of high priority.

In 1984 the injection of barium particles into the solar wind on the Active Magnetosphere Particle Tracer Explorers (AMPTE) mission was carried out as an "artificial comet" experiment to elucidate aspects of the plasma interaction with the comet. In the future, the placement and operation of platforms in space will provide opportunities to conduct analogous simulation studies of other facets of cometary phenomena involving more realistic materials. These studies should be conducted to provide assessments of two interesting questions: the origin of daughter molecules and ions from putative parent species in either the gas or the dust emitted from comets, and the dynamical evolution of cometary dust mantles, aggregates, and grains as a function of their physical properties and chemical composition.

Two types of experiments are envisioned: releasing water vapor and selected gases, singly or as mixtures, from canisters and releasing a meter-sized ball of water ice laden with either gas or dust or both. The measurement objective in both types of experiments would be to follow spectroscopically in the ultraviolet, visible, or infrared (or some combination of wavelength regions) the changes in composition in the coma and tail as functions of time and distance from release. An additional objective in the case of the ice ball would be to determine the physical evolution of the ice and dust with respect to chemical reactions at the surface and to formation of dust mantle, ejection of grains or grain aggregates from the surface or interior, and their disaggregation and dissipation over time. Embedded thermal sensors could be used to follow the thermal evolution of the interior.

The interaction of the unattenuated solar flux with the volatiles and dust would be examined, as would the processes of sublimation and photolysis. The interaction of the Earth's magnetic field and ionosphere moving past the sublimed and ionized gases at about 7 km/sec could be studied as analogs to processes that occur at a real comet because of solar wind interaction with the cometary ionosphere.

For both types of experiments, selecting the mode(s) of observation (ground-based, airborne, spaceborne, or combinations thereof) to follow the resulting course of chemical evolution of nucleus, coma, and tail would have to take into account the time scales available for observations of each feature; the requirements for spatial, spectral, and temporal resolution; and the need to synchronize the release with the onset and continuation of observations.

One major problem in either type of experiment is the interference of the Earth's atmosphere. The coma of an artificial comet cannot be studied at the orbit of the Space Station (~300 km) because of the reactivity of a large flux of oxygen atoms ($\sim 4 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$) and a somewhat smaller flux of nitrogen molecules. By comparison, the flux of photons of wavelength less than 2000 Å is only $1.1 \times 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$. Therefore, the gas or ice ball should be released at an altitude of ~1000 km. At this altitude, the fluxes of oxygen and hydrogen atoms are only $\sim 6 \times 10^9$ and $\sim 3 \times 10^{10} \text{ cm}^{-2} \text{ sec}^{-1}$, respectively; the flux of thermal ions is $\sim 6 \times 10^9$ and of 100 MeV photons only $10^3 \text{ cm}^{-2} \text{ sec}^{-1}$. All of these are much smaller than the flux of photons with wavelength less than 2000 Å; and, therefore, the coma chemistry is not likely to be much affected by them.

For the gas-release experiments, several canisters, each containing a selected pressurized gas, would be placed at the appropriate orbit. The water canister should be heated to a high temperature in order to supply water vapor at the required rate. The valve of each canister should be operated separately, enabling the formation of various gas mixtures and also imitating to some extent the gradual release of gases from a gas-laden ice ball.

The gases selected for release would depend on the theoretical parent-daughter relationships that are being tested and could include carbon monoxide, carbon dioxide, methane, acetylene, ammonia, hydrogen cyanide, and acetonitrile, among others. While lacking a full complement of gases, ices, or other grains, these experiments would necessarily be incomplete simulations. On the other hand, ground-based experiments would be similarly limited; moreover, the simulations of the vacuum, volume, and time scales of the inner coma would be impossible in the laboratory.

Formation of a gas-laden ice ball may be achieved by expanding a mixture of water vapor with various gases, through a nozzle, into a vacuum chamber to produce a snow, which may then be consolidated by compaction to the desired extent. Dust particles could be injected simultaneously and mixed with the snow. Alternatively, quantities of water vapor and gases could be frozen on a cold surface and continuously scraped from it, until a large enough quantity is accumulated to make into the ~ 1 -m (or larger) ice ball. An ice ball of this size is calculated to last for about 10^5 sec (about 28 hours) under full solar heating.

Ices could be prepared at various densities and at different temperatures corresponding to amorphous or crystalline states. Recent laboratory experiments indicate that, depending on the temperature of formation and thermal history of the ice, gases may be occluded in amorphous or crystalline forms of ice; different gas-release characteristics may prevail, depending on the ice phase, in some cases accompanied by ice grain ejection. Preservation of such sites would be essential for study. If formed at temperatures lower than 80 K, the ball should be kept in a dewar cooled by liquid helium, itself enclosed in a dewar of liquid nitrogen, until the time of release.

In the cases where dusts of either silicate or carbonaceous composition or both were embedded in ice, the choice of material to simulate the dust would necessarily be model-dependent. Candidate materials for carbonaceous grains, for instance, could be amorphous carbon, polymers of HCN, coal dust, and terrestrial kerogens, among others.

Experiments with an ice ball could not simulate the heterogeneity of physical and chemical composition or the irregularity in the distribution of surface-active sites that were actually observed in comet Halley. Determining how simpler model systems behave, however, would be a prerequisite for gaining understanding of the more complex systems.

Precursor laboratory simulations should be conducted in a large, ground-based, high-vacuum chamber where an ~ 1 -m ice ball could be formed and subjected to heating by infrared or xenon arc lamps.

When compared with the large body of observational data now available as a result of studies of comet Halley, it is expected that observations made on an artificial coma and tail produced by a gas-laden ice ball in Earth orbit, together

with observations obtained on a coma produced by gas-release experiments and in large-scale laboratory experiments, will contribute substantially to our knowledge of the structure and composition of cometary nuclei. Among the questions that will be addressed are: How are gases occluded in the nucleus and how are they released? What gases or grains and what sequence of their release could produce the species distribution observed in real cometary comae? What is the contribution of gas-laden ice grains in the coma to its chemistry? What properties of grains are conducive to the formation of dusty mantles?

5.4 Microbial Survival in Space

Panspermia is the concept that life on Earth arose not *de novo* but from an inoculum that reached the Earth from space. If panspermia were true, the problem of the origin of life would be transferred from the relatively known environment of Earth to a relatively unknown environment elsewhere. If panspermia has occurred it is required that

1. Life arose somewhere else in the universe and flourished.
2. Some of the living organisms in this location left their origin and entered outer space.
3. Some of these latter organisms survived space travel and reached Earth.
4. Some of these surviving organisms penetrated the Earth's atmosphere in viable form.
5. Some (or at least one) of these viable organisms found conditions favorable on Earth and flourished.
6. The descendants of this xenobiont led to the vast array of organisms on Earth today.

It would, of course, be difficult to prove unambiguously that panspermia occurred. However, it might be possible to determine by measurement, calculation, and experiment how likely it is that panspermia could occur, that it is impossible to disprove panspermia experimentally, or that the probability of panspermia is vanishingly small. (In this discussion, directed panspermia is not being considered as there is yet no evidence that intelligent life exists in the universe outside Earth.)

In light of the above scenario, there are several approaches for investigating certain aspects of the concept of panspermia:

1. Measurement or calculation of the rate at which organisms could escape from a planet
2. Measurement or calculation of the rate at which organisms would be killed during space travel
3. Calculation of the time it would take for xenobionts to reach Earth from various sources in outer space
4. Calculation of the concentrations of xenobionts that might be expected in the Earth's orbit

5. Calculation, using results from 3 and 4, of a flux rate for xenobionts reaching the Earth's surface, permitting determination of the experimental requirements that would be needed for detecting by direct measurement any putative xenobionts

One critical problem in carrying out the above scenario is that material collected in Earth orbit (Chapter 4) may also contain viable organisms derived from Earth (perhaps ejecta attached to volcanic debris). Thus, it would be extremely important to determine the flux rate of organisms from Earth into space. The final result of such studies might be that viable organisms found in Earth orbit are most likely to have been derived from the Earth's biosphere. A direct microbiological test of panspermia with existing tools is difficult but possible: for example, one could search for the presence of novel amino acids or nucleosides.

Microbial survival is one of several parameters that can be used to put probability boundaries on the hypothesis of panspermia. While one can hypothesize that the evolution of life on other planets might have led to organisms more tolerant to the conditions of interstellar space than the terrestrial creatures with which we are familiar, such a hypothesis cannot be tested at present. This discussion is thus organized around the notion that extraterrestrial organisms will be fundamentally similar to those found on Earth. The proposed experiments are concerned with determining the survival potential of terrestrial organisms subjected to conditions characteristic of space. Since the major environmental variables in space are radiation flux (particularly ultraviolet), vacuum conditions, and low temperatures, these parameters should be critically examined. The studies can be organized around three general areas or questions:

1. To what extent does an organism's physiological state affect its survival potential?
2. What is the range of resistance to ultraviolet and other injurious factors among microbes isolated from terrestrial and aqueous environments?
3. What are the critical factors that affect any resistance to the conditions found in space?

Some experimental work has been done in each of these areas, including carrying microbes into space aboard Spacelab, but additional ground-based studies are needed to enable proper planning for further *in situ* space-based experiments. Ground-based studies have the advantage that they are relatively inexpensive and the experimental design is flexible. Thus, use of space simulations and atmospheric controls should allow various hypotheses dealing with space survival to be tested. These hypotheses can be expected to evolve to a point at which they could be developed as experiments or experimental programs suitable for further testing in space. However, since a satisfactory, ground-based simulation of the complex interplay of all of the environmental factors of outer space is difficult, if not impossible, to attain, the performance of experiments on living microorganisms in Earth orbit is required to properly study the viability of microbes in space.

To determine the relation between physiological state and viability, the following parameters should be examined:

1. The effect of the particular portion of the growth cycle (i.e., exponential vs. stationary phase cells, including cells maintained for extended periods in the stationary phase)
2. The effect of the growth medium (i.e., complex vs. simple)
3. The effect of the type of energy-generating processes (i.e., fermentative vs. respiratory)
4. Resistance to oxidation (i.e., the presence of superoxide dismutase and/or catalase)
5. The effect of lyophilization on resistance

Since exposure to the low temperatures and vacuum of outer space would effectively lyophilize microbial cells, an examination of the role of the state of hydration on resistance and survival is of paramount importance. Experiments should be planned so as to consider synergistic effects. The current literature contains much information on the effect of various physical and chemical factors on the survival of microorganisms. However, many of these studies were carried out with "hydrated" cells and are probably irrelevant to the lyophilized state. The degree to which hydrated and dehydrated cells exhibit different sensitivities to various agents should be thoroughly tested. Another particularly important parameter is temperature. The effects of very low temperatures on resistance and survival should be studied.

The selection of appropriate test organisms should be made with care. Ideally, one should employ organisms that are easy to handle and which are well known with respect to their genetics, nutrition, and physiology. In addition, organisms exhibiting greater than usual resistance should be considered. The following two organisms are possible prototypes:

1. *Escherichia coli*, a gram-negative heterotroph with about average powers of resistance and capable of reasonable survival in nature
2. *Bacillus subtilis*, a gram-positive heterotroph, the vegetative cells of which are no more resistant than those of *E. coli*, but which produces a structure, the endospore, capable of surviving extremes of temperature, desiccation, and nutritional deprivation

Throughout the 3.5 to 4 billion years of life history on Earth, adaptation to conditions comparable to outer space seems never to have been required. In view of the lack of perfectly suitable test systems, one could turn to the use of organisms adapted to growth or to survival, at least in extreme regions of the biosphere such as in soil or rock from deserts or Antarctica, or in the upper layers of the atmosphere. Airborne microbes commonly are in a resting or temporarily inactive state, either as a spore with built-in resistance mechanisms against environmental extremes or modified by desiccation and starvation. They are represented by endospores of bacteria and spores of actinomycetes, fungi, ferns, mosses, pollen of flowering plants, and cysts of protozoa. Some of them are

especially adapted for dissemination over the biosphere. Endolithic life forms, such as cyanobacteria, algae, fungi, and lichens of unusual organization, have been detected inside rocks from the Antarctic dry valleys as well as inside desert sandstone. They represent an example of a simple ecosystem with a favorable microclimate surrounded by an extreme environment of low humidity, temperature extremes, and a high influx of solar radiation. Resistant organisms could be sought by the wholesale exposure to extreme conditions of samples taken from a variety of such inhospitable localities on Earth.

The study of any given organism (or small group of organisms) has the disadvantage that the results obtained may not be representative of the total picture. Misleading "dogma" can be established through the rigorous and in-depth study of a few easy-to-handle organisms. Therefore, the variability in levels of resistance for a variety of microorganisms should be systematically examined.

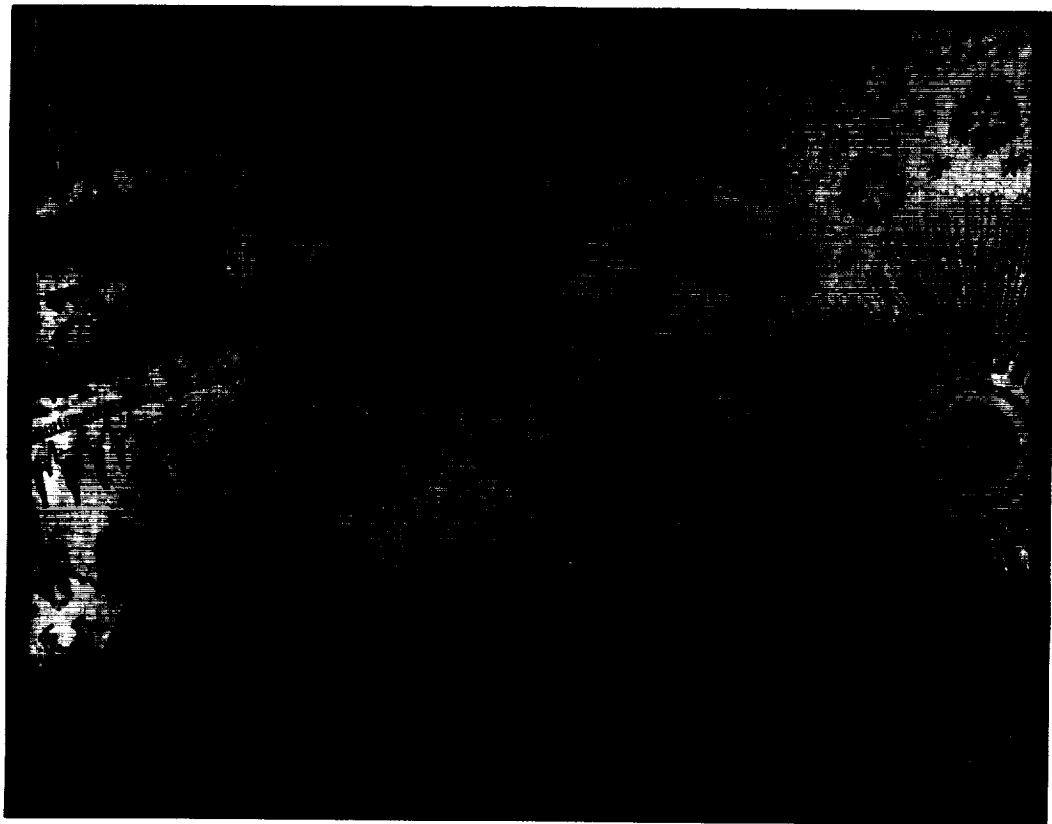
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Chapter VI

Summary of Proposed Experiments

The next several decades offer many exciting opportunities to conduct exobiological observations and experiments in Earth orbit, and to attack a wide variety of questions that are not directly amenable to ground-based studies. This summary highlights the most important aspects of the exobiology research identified in this report, prioritizes the various projects, and indicates which can be pursued with facilities available now and which must wait for capabilities that are planned for the future. The order in which the different research topics are discussed in the Observational Exobiology section indicates, by the consensus of the members of this Workshop, their relative importance to exobiology. The ordering within the other two sections, Cosmic Dust Collection and *In Situ* Experiments, does not imply any prioritization, nor is the order in which the three major sections appear meant to imply anything about their relative importance. These selected experiments are for Earth-orbital activities only, and they augment the very strong interests of the exobiology community in ground-based research and solar system missions.

6.1 Observational Exobiology

Since life, as we know it, is a planetary phenomenon, it is of utmost importance to know whether planets exist outside our own solar system. The orbital observatories of the next few decades should allow us to answer this fundamental question. In addition, we anticipate that the greatest increase in our understanding of the origin and evolution of the biogenic elements will come from the use of telescopes above the Earth's atmosphere, opening up the wavelength region from the far infrared to the submillimeter. This portion of the spectrum provides unique information about many molecules and particles in diverse

A famous early 20th century engraving (1911) erroneously thought to be a 17th century woodcut of a Medieval astronomer passing through the sphere of the stars to see the mechanisms of the Ptolemaic universe beyond. (Courtesy of Science Graphics, Tucson, AZ.)

cosmic environments and to date is almost completely unexplored. High sensitivity, in addition to good spatial and spectral resolution, will be extremely important, as will the laboratory and theoretical studies needed to correctly interpret the new observational data.

6.1.1 Detection of Extrasolar Planetary Systems

The best opportunity for conducting a systematic survey of the nearest stars for massive, long-period planets is a dedicated astrometric telescope to be mounted on the upper boom of the Space Station. Alternative approaches such as searches for short-period planets will require technical breakthroughs to develop a double differential photometer, or a long-lived platform to monitor thousands of stars for periodic occultations may be accommodated by Space Station. The detection of extrasolar planetary systems is best pursued at optical and near-infrared wavelengths. Earth-orbital observations are crucial as the Earth's atmosphere imposes severe limitations on the ability to either directly detect a planetary companion to a star or to indirectly deduce the presence of a planet from its influence on the stellar motion or apparent brightness. While the HST will be able to measure, with observations taking minutes, the relative position of a nearby star that is as accurate as can be obtained with modern detectors and hours of ground-based telescope time, and it will have the orbital longevity and mechanical stability needed for such an astrometric search program, it is unlikely that sufficient time will be allocated for a systematic search for extrasolar planetary systems.

The logical followup to an astrometric detection of an extrasolar planet is its direct detection. Once again, this is best done from observatories in Earth orbit. The HST will provide the best opportunity in the near term to attempt imaging any extrasolar planets detected astrometrically or tentatively identified from ground-based observations. Imaging is easier at near-infrared wavelengths where the contrast ratio of planet and star is larger and either the NICMOS infrared spectrometer or the imaging Michelson interferometer selected for the second generation of HST instrumentation may provide a capability to do just that. If either SIRTf or ISO prove to be capable of producing a "superresolution," they may be able to image the outer planets around nearby stars. FIRST or LDR should eventually provide the necessary better resolution, but a free-flying infrared interferometer will be required to provide imaging capabilities for more distant stars.

6.1.2 The Solar Nebula and its Analogs

Observations of regions of star formation are important to exobiology in two ways. First, they will determine how stars hospitable to the origin of life are

formed, and second, they are necessary to make estimates of the likelihood of planet formation. Because of the clouds of dust obscuring star-forming regions, protostellar observations must be made principally at far-infrared and longer wavelengths. Studies of the far-infrared continuum and low-resolution spectroscopy will help determine the quantity and composition of material available for the formation of planets. High-spectral- and high-spatial-resolution observations at submillimeter and far-infrared wavelengths are needed to identify the molecules present in the gaseous state; these can be used to determine the nature of the physical environment and to investigate the link between organic chemistry in the dense molecular protostellar clouds and the protostellar nebula. In order for the far-infrared-continuum observations to be sufficiently sensitive, a cryogenically cooled telescope must be employed. Of lesser importance, ultraviolet studies of objects in the late stages of star formation, when the obscuring dust clouds have been blown away, can yield information on the radiation environment in planetary systems in the era of the origin of life. All of the observations listed here are strongly affected by atmospheric absorption, and thus are best made with orbiting observatories.

The contribution of biogenic and other heavy elements from stars to the interstellar medium is also of exobiological importance. This happens late in the life of a star, either as grain formation and ejection in the atmospheres of giant stars, or in supernovae ejecta. To a lesser extent, it also occurs during the main-sequence stage of stellar evolution through the action of stellar winds (for example, the solar wind). Observations of these evolved objects are best made in the visible and near infrared.

The first-generation instruments on the HST are capable of performing only the ultraviolet and visible observations discussed here. SIRTf is necessary for the other studies mentioned. More detailed work, especially in the high-resolution studies of molecular and atomic lines, requires LDR for its high sensitivity and spatial resolution, which is necessary to determine the composition and structure of matter within these energetic systems.

6.1.3 Solar System Observations

While we recognize the importance of measurements by direct missions to solar system objects, three broad areas of solar system observations have been identified as holding promise for exobiological studies from Earth orbit. These are primarily related to the identification of biogenic elements and complex molecules in primitive bodies and in the atmospheres of the giant planets and satellites. Significant progress is expected, particularly from the use of the HST. Nonetheless, many species of interest will remain undetectable until the development of sensitive orbiting telescopes and spectrographs for the spectral range from the far-infrared through millimeter wavelengths.

Comets and asteroids present two challenges for study from Earth-orbiting observatories. Studies of cometary comae are similar to the atmospheric observations of the giant planets described later, although the lack of pressure broadening makes very high spectral resolution both extremely useful and desirable; this can be obtained with LDR and/or a higher-resolution SIRTf spectrometer than is currently planned. Determining the composition of the solid (ice or mineral) surfaces can be performed by means of reflectance spectroscopy, at reasonably high resolution, in the infrared. Some of this work can be done in the near infrared when HST acquires this capability, but most likely an infrared orbiting observatory such as SIRTf or ISO will be required. The WUPPE that is part of the ASTRO Shuttle package will allow the size and composition of the cometary dust to be inferred from the percentage of polarization in scattered light from 1300 to 3300 Å.

The objectives for Titan, the only known planetary satellite with a significant atmosphere, are similar to those below for the giant planets. Because of the very small angular size of the satellite, the measurable flux is much smaller than that for the planets, and initial observations may have to await the development of more sensitive, second-generation HST instruments.

For the giant planets the need is to increase knowledge of the inventory of trace molecular species in the predominantly hydrogen atmospheres and to determine, using line-shape measurements at high spectral resolution, the vertical and meridional distributions of these species in the atmosphere. Isotope ratios should also be determined for the most abundant molecules. When HST becomes operational it will permit high-resolution studies of molecules detectable in the ultraviolet and visible and, in addition, will allow these studies to be extended to Uranus and Neptune. ASTRO will provide limited observations of solar system targets, but should add significant information about their atmospheric composition. Further progress will require high-resolution infrared, submillimeter, and millimeter observations from space using platforms such as SIRTf, ISO, or LDR. Determination of abundances from such observations will need extensive laboratory data currently not available.

6.1.4 Molecules in the Interstellar Medium

The study of molecules in interstellar space is an important component of exobiology. Three important questions to be answered in this field are the extent of chemical evolution throughout the universe, the availability of biogenic elements, and the existence of molecules such as water and organic compounds. The extent of chemical evolution can be determined by spectroscopic studies of complex molecules in the gas phase of interstellar clouds, especially in the infrared and the millimeter, and by studies of interstellar dust particles in the infrared, visible, and ultraviolet. In the near future, most detailed observations of molecules will be undertaken via ground-based millimeter- and

submillimeter-wave telescopes. However, infrared spectra are especially important in determining complex molecular signatures; because of atmospheric interference, such space-based observatories as SIRTf and LDR will be crucial in this regard. A high-resolution spectrometer on SIRTf would be especially useful for precise molecular identification. A vigorous program of laboratory spectroscopic studies is necessary to complement the observational program because the laboratory spectra of many important interstellar molecules have not yet been fully studied.

The availability and relative abundances of biogenic elements can be determined by observational studies directed at either atoms or molecules. The determination of the relative abundances of carbon and oxygen in various sources is important because it is thought by some investigators that molecular complexity can occur only in carbon-rich regions. An inventory of the biogenic elements in external galaxies would be especially interesting and would be aided by space-based observatories in all wavelength regions.

Finally, the existence of water and organic compounds can be investigated via spectroscopic studies in a variety of wavelength regions, especially the submillimeter and infrared, depending upon the excitation conditions in the source. It is obvious that space-based observatories such as HST, LDR, and SIRTf will aid immeasurably in the search for these species. Whether molecules such as these are widespread in our own and other galaxies is intimately related to the probability that life exists elsewhere.

6.1.5 Time Scales

The order in which observations of interest to exobiologists are performed and the pace at which our understanding increases will be determined by the timetables established within NASA and ESA for the development of the orbital facilities identified earlier. The following list represents the current best estimate of the order of implementation of the telescopes judged most useful to observational exobiology. The observations listed under each spacecraft reflect the priorities outlined above.

Hubble Space Telescope (HST): NASA 1989

1. Astrometric and coronagraphic searches for extrasolar-system planets to be augmented by second-generation infrared instrumentation in 1994
2. Ultraviolet observations of young, stellar objects—determination of the radiation environment in early stages of planetary systems
3. Visible and near-infrared observations of grains in stellar atmospheres
4. High-resolution spectroscopy (ultraviolet/visible) of planetary atmospheres, comets, and asteroids; imaging of planets at wavelengths of specific molecular bands

ASTRO 1: NASA 1989

1. Spectroscopy (500–3200 Å) of planetary atmospheres
2. Ultraviolet imaging of planets and comets in selected bands
3. Ultraviolet polarimetry of dust in comets and in interstellar space
4. Extinction-curve measurements to study size and distribution of interstellar grains

Space Station—Block I: NASA 1995

1. Dedicated astrometric telescope
2. Service and instrument changeout on free-flying orbiting telescopes
3. Construction and servicing of later generations of orbiting telescopes

Space Infrared Telescope Facility (SIRTF): NASA 1996

Infrared Space Observatory (ISO): ESA 1992

1. Possible direct imaging of extrasolar planets using superresolution
2. High-spectral-resolution observations of atoms and molecules in star-forming regions, e.g., water
3. Continuum and low-resolution observations of dust in star-forming regions
4. Observations of complex organic molecules
5. Continuum and low-spectral-resolution studies of grain formation and ejection from stellar atmospheres in the late stages of stellar evolution
6. Continuum and low-resolution studies of grains in supernovae ejecta
7. Molecular spectroscopy of solar system planets, satellites, comets, and asteroids
8. Thermal emission from dust in comets
9. Reflectance spectroscopy of solid surfaces (asteroids) and ices (comets)

Far Ultraviolet Spectroscopy Explorer (FUSE): NASA 1996 (Joint with ESA under the name Lyman)

1. High-resolution, extreme-ultraviolet spectroscopy of the interstellar medium and the intergalactic medium

Large Deployable Reflector (LDR): NASA 2000

Far Infrared Space Telescope (FIRST): ESA 1995

1. Direct imaging of extrasolar planets
2. High-resolution studies of accretion shocks surrounding protostellar nebula
3. High-spectral-resolution observations of molecules in star-forming regions
4. Studies of molecular oxygen and water in many transitions in regions of star formation and planets

In closing, we note that while the next few decades offer exciting opportunities for observational exobiology, even more exciting prospects lie just a little farther in the future. For example, having detected examples of extrasolar

planets, exobiologists would no doubt wish to study them in detail. This will require a whole new generation of telescopes or arrays of telescopes in high orbit or on the lunar far side with capabilities in excess of the near-term orbiting systems. There is much to be learned.

6.2 Cosmic Dust Collection

Collection of cosmic dust is important to exobiology because collectable dust particles are samples of comets and asteroids, primitive bodies that are likely to preserve compounds that formed during or before the origin of the solar system. Cometary particles are of particular interest because comets probably formed in the coldest, most-remote, regions of the solar nebula. Collection from Earth orbit can provide an unbiased sample of nanogram to microgram particles that complement meteorites and samples of extraterrestrial dust in the stratosphere. The most exciting aspect of meteoroid collection from orbital platforms is the active measurement of impact velocity and directions to identify the sources of individual collected particles.

6.2.1 Capture Techniques

The unintentionally captured meteoroids collected from returned Solar Max surfaces have shown that analyzable material can be collected even with simple materials such as aluminum sheet metal and multilayer plastic thermal blankets. Capture experiments were recently flown on Salyut and currently are being exposed on LDEF. They were specifically designed to collect meteoroids, and their results will play a role in developing future experiments. The development of special capture materials or cells for the collection of the biogenic material in analyzable form is needed for exobiology. For example, special metal capture cells where low-atomic-weight elements could be recondensed on cell walls following hypervelocity impact could be used—retention of some elements may require a “getter.” The development of clean cells made of appropriate materials should lead at least to the capture of enough material to determine elemental hydrogen, carbon, and nitrogen abundances and isotope ratios. The hydrogen isotopic composition is of particular importance because large isotope effects have been seen for this element in interplanetary dust samples. No previous experiments exist for the capture of light elements, and the development of capture cell techniques will involve laboratory simulation experiments (using dust accelerators and lasers) and actual orbital collection experiments.

The ultimate particle collection experiment is the so-called “intact capture” in which the particle, or at least parts of the particle, are collected without heating or significant modification. One approach is to use “soft” collection substrates where the particle is decelerated slowly. Soft materials include porous targets and gas cells. Experiments under way are promising; porous targets can

definitely be used for intact collection of particles impacting at less than 6 km/sec. The lowest impact velocity on an orbiting collector is 3 km/sec. Collectors of this type that do not contain hydrogen, carbon, nitrogen, or oxygen and hence will not contaminate samples, will have to be developed. The development of soft collection substrates involves dust accelerators and actual flight exposures. In the long term, it is hoped that electromagnetic decelerators can be developed so that meteoroids can be collected, ideally, with no heating at all. Near-term work in this area will be to develop a prototype design and to conduct a feasibility study.

6.2.2 Orbital Parameter Measurement

An electronic technique to measure the impact velocity and direction of particles was used on Pioneers 8 and 9 and on the LEAM experiment placed on the Moon during Apollo 17. Other techniques have been suggested and investigated in at least a casual way. It is critical for the future of meteoroid collection in Earth orbit to fully develop at least one approach that can be used with a practical system for the collection of 10- to 250- μ m particles. The speed and impact angle should be measured to an accuracy of a few percent so that the orbits of collected samples can be determined with sufficient accuracy. There appear to be no technological hurdles to achieving this accuracy, and the development will probably be more of an adaptation and refinement of existing techniques.

6.2.3 Laboratory Analyses

The collectable cosmic dust samples will be small and techniques for their analysis must be refined. As examples, isotopic, mass spectrometric, gas chromatographic, and spectroscopic analyses are possible for samples this small, but techniques to do so have not been adequately developed. Laboratory techniques that could be refined for this study include mass spectrometry, gas chromatography, Auger spectroscopy, microESCA (Electron Spectroscopy for Chemical Analysis), Secondary Ion Mass Spectrometry (SIMS) microprobe, and a variety of other techniques, including energy-loss spectroscopy. Developments of such microanalytical techniques would also be of considerable value for the analysis of meteorites, interplanetary dust, and samples returned from comets and Mars.

6.2.4 Flight Exposures

Development and implementation of the new generation of orbital dust collectors will require several types of long-exposure flight opportunities. For the development of techniques, a square meter exposed for several months to a year

would be adequate in many cases. Ultimately, the collection of large or otherwise rare particle types will require several square meters exposed for at least a year. On an operational Space Station one can envision a 10- to 100-m² area exposed continuously with astronaut recovery of selected modules that are hit. Development of a contamination monitoring system for the collection environment should take place in parallel with any collection program.

6.3 In Situ Investigations

Spacecraft in Earth orbit, in particular the Space Shuttle and Space Station, allow experiments to be done that are not possible on the ground. Space laboratories provide a unique combination of conditions that cannot be duplicated in terrestrial laboratories. Four different types of experiments have been identified as being able to take advantage of the special opportunities provided in Earth orbit; three of these are highlighted here.

6.3.1 Studies of Suspended Dust Grains

Detailed studies of the fundamental physical and chemical processes leading to the formation, condensation, and aggregation of dust grains, and the processes occurring on the surfaces of grains in circumstellar shells, in interstellar dust clouds, and in prestellar nebula, can be best done on a space platform in Earth orbit. Such experiments are directly relevant to the growth of planetesimals and, ultimately at least, the terrestrial planets. Increasing interest is being shown in the constituents of these environments, and the mechanisms of molecular and grain synthesis that may occur there. Whether organic molecules or carbonaceous grains that originated in these environments could have survived intact during the accretion of the Earth is not known. However, the analysis of meteorites and cosmic dust clearly shows that molecules and carbonaceous grains of extraterrestrial origin can survive entry into the atmosphere of the contemporary Earth. The proposed experiments may therefore also be relevant to Earth-based exobiological research: what organic compounds should one use in laboratory simulations of reactions that may have been important for the origin of life?

6.3.2 Artificial Comets

Interest in comets is presently intense as the many exciting results from the study of comet Halley are being analyzed. As is normal in scientific investigations, many new questions are arising from these studies. A deeper understanding of the chemical and physical processes that occur at the interface between gas-and-dust-laden ice and space, under the influence of solar heating, is not only

of interest in itself, but will help in planning for future comet sample return missions. An incremental increase in the depth of understanding of cometary processes could be achieved by the study of artificial comets in space. Two types of experiments are envisioned, one in which gas is released and monitored to simulate the coma and tail, and one in which a dust-and-gas-laden ice ball is released and monitored to simulate the nucleus and its immediate vicinity. Such experiments in space are the logical next step in the study of comets, bodies that contain much information of interest to exobiologists concerning the early history of the solar system and the environment of the early Earth.

6.3.3 The Survival of Microorganisms in Space

While most scientists are convinced that life evolved on Earth from nonliving matter, the idea that life evolved elsewhere, traveled across space, and inoculated our own world is an intriguing one. One of the requirements of this panspermia hypothesis is that microorganisms can survive in the space environment. As this environment cannot be simulated on the ground, the viability of microorganisms in space must be tested in space. Therefore, a variety of microorganisms should be exposed to the space environment and their viability determined under differing, controlled conditions. Such studies are relevant to exobiology in the strict sense of the word, and can provide an experimental test of the panspermia hypothesis; they are important to biology in providing new information on the adaptability of life to extreme environments.

Appendix A

ACRONYMS AND ABBREVIATIONS

AMPTe	Active Magnetosphere Particle Tracer Experiment
AO	Announcement of Opportunity
AU	Astronomical Unit
AXAF	Advanced X-ray Astronomy Facility
CCD	Charge-Coupled Device
COBE	Cosmic Background Explorer
CRAF	Comet Rendezvous Asteroid Flyby
ELV	Expendable Launch Vehicle
ESA	European Space Agency
ESCA	Electron Spectroscopy for Chemical Analysis
EURECA	European Retrievable Carrier
EUVE	Extreme Ultraviolet Explorer
FIRST	Far-Infrared Space Telescope
FOC	Faint Object Camera (on HST)
FOS	Faint Object Spectrograph (on HST)
FTT	Fischer-Tropsch type (synthesis)
FUSE	Far Ultraviolet Spectroscopy Explorer
GAS	Getaway Special (on Space Shuttle)
GRO	Gamma Ray Observatory
GSFC	Goddard Space Flight Center
HH	Herbig-Haro (object)
HR	Hertzsprung-Russell diagram of stellar luminosities plotted against effective stellar temperature
HST	Hubble Space Telescope
HUT	Hopkins Ultraviolet Telescope (on ASTRO)
IMS	Imaging Michelson Spectrometer
IR	Infrared region of the electromagnetic spectrum
IRAS	Infrared Astronomical Satellite
IRIS	Infrared Interferometric Spectrometer (on Voyager)
ISO	Infrared Space Observatory
IUE	International Ultraviolet Explorer
KAO	Kuiper Airborne Observatory
LDEF	Long Duration Exposure Facility
LDR	Large Deployable Reflector
LEAM	Lunar Ejecta and Meteorites

MRPS	Medium-Resolving-Power Spectrometer (on LDR)
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
OMV	Orbital Maneuvering Vehicle
OTV	Orbital Transfer Vehicle
OVLBI	Orbiting Very Long Baseline Interferometer
PAH	Polycyclic Aromatic Hydrocarbon
PVDF	Polyvinylidene Fluoride
SETI	Search for Extraterrestrial Intelligence
SIMS	Secondary Ion Mass Spectrometry
SIRTF	Space Infrared Telescope Facility
SOFIA	Stratospheric Observatory for Infrared Astronomy
SSEC	Solar System Exploration Committee
STS	Space Transportation System
TOF	Time of Flight
UV	Ultraviolet region of the electromagnetic spectrum
WFC	Wide Field Camera (on SIRTF)
WF/PC	Wide-Field/Planetary Camera (on HST)
WUPPE	Wisconsin Ultraviolet Photopolarimetry Experiment (on ASTRO)
XMM	X-ray Multiple Mission

Appendix B

CHARACTERISTICS OF ORBITAL OBSERVATORIES					
Instrument	Wavelength	Field of view	Resolution		Sensitivity
			Spatial	Spectral $\lambda/\Delta\lambda$	
IRAS ^a					
Survey array	8-15 μm	0.75'x4.5'	40"X30"	2	0.12 Jy
	15-30 μm	0.75'x4.5'	40"X30"	2	0.07 Jy
	30-50 μm	1.5'x4.7'	64"X46"	2	0.18 Jy
	50-120 μm	3'x5'	2'X84"	3	0.43 Jy
IUE					
Short-wavelength prime camera	1165-2126 Å	16'	3" or 10"X20"	10 ⁴	---
	1150-2000 Å	16'	3" or 10"X20"	200-333	---
Long-wavelength prime camera	1845-3230 Å	16'	3" or 10"X20"	10 ⁴	---
	1825-3300 Å	16'	3" or 10"X20"	304-550	---

^aCatalog of point sources and photographic material on extended regions of emission is available for follow-on studies.

Hubble Space Telescope (HST)						
Wide-field camera f/12.8	42 filters, 3 objective gratings, 3 polarizers	2.67'	0.10"	10-300	9.5-28 mV	
Planetary camera f/30	11000-11150 Å	1.15'	0.05"		8.5-28 mV	
Faint-object camera f/96	Many broad filters, 2 objective prisms, 3 polarizers	11"	0.02"	50-100	21-28 mV	
f/48	6000-1200 Å	22"	0.04"		21-28 mV	
Faint-object spectrograph	Grating wheel, prism, and polarizer	0.1-4.3" (1 of 12 apertures)	---	10 ³	19-22 mV	
	7000-1150 Å	0.1-4.3"		10 ²	22-26 mV	
High resolution spectrograph (minimum time sample = 0.025 sec)	3200-1100 Å	0.25" or 2.0"	---	10 ⁵	<11 mV	
	3200-1100 Å	0.25" or 2.0"	---	2X10 ⁴	<14 mV	
	1700-1100 Å	0.25" or 2.0"	---	2X10 ³	<17 mV	
High-speed photometer (minimum time sample = 16 μsec)	Broad filters and polarizer	0.4" or 1.0" or 10"	---	---	<24 mV	
	8000-1200 Å					
Fine guidance sensors	4670-7000 Å	3 sensors 4'X17"	0.002"	None: white light int'fr	4-17 mV	

ASTRO						
Hopkins ultraviolet telescope	850-1850 Å	40'	---	300-600	3 Jy	
Ultraviolet imaging telescope	425-925 Å 1200-1700 Å 1250-3200 Å 2 cameras with 6 filters each	2"	2"	Few	5-25 mV in 30 min	
Wisconsin ultraviolet photopolarimeter experiment	1400-3200 Å	3.3'x4.4'	2"	350-800	mV < 16	
COBE						
Far-infrared absolute spectrometer	100 μm-1 cm polarizer	7°	---	<20	13 Jy	precision of spectrum is 1/1000 of peak
Differential microwave spectrometer	31.4 GHz 53 GHz 90 GHz	7° 7° 7°	--- --- ---	--- --- ---	Differential between horns Δ = 0.0003 K Δ = 0.00015 K Δ = 0.00015 K	
Diffuse infrared background experiment	10 bands 1-300 μm (J, K, L, M, and 4 IRAS bands + 2 longer)	1°	---	1-20	100 Jy	

EUVE						
4 grazing incidence imaging telescopes	70-180 Å 160-300 Å 400-500 Å 600-750 Å 100 Å 250 Å	5° 5° 4° 4° 2.1° 2.1°	1' 1' 30" 30" 30" 30"	--- --- --- --- --- ---	5 μJy 100 μJy 800 μJy 700 μJy 1 μJy 6 μJy	
Spectrometer	70-750 Å	2.1° or 0.1° × 1°	1'	100-200	30-200 μJy	
GRO						
High-energy survey telescope	>40 MeV	Degrees	2'	7	10 ⁻⁷ P/cm ² /sec	
Low-energy scintillation counters	0.3-10 MeV	Degrees	30'	4	10 ⁻⁵ P/cm ² /sec	
Medium-energy telescope	7-50 MeV	Degrees	30'	4	10 ⁻⁵ P/cm ² /sec	
Low-energy burst monitor	1-10 MeV	Omni- directional	6'			
High-resolution nuclear spectrometer	0.1-10 MeV	Degrees	---	250	10 ⁻⁵ P/cm ² /sec	

AXAF						
High-resolution imaging	0.1-10 keV	30'	0.5'' $\Delta t = 10 \mu\text{sec}$	25		7×10^{-10} Jy
Moderate-resolution imaging	0.1-10 keV	1°	10'' $\Delta t = 10 \mu\text{sec}$	5		7×10^{-10} Jy
High-resolution spectrograph	0.1-10 keV	1°	10'' $\Delta t = 10 \mu\text{sec}$	1000		7 μJy
Moderate-resolution spectrograph	0.1-10 keV	1°	10'' $\Delta t = 10 \mu\text{sec}$	40		
Polarimeter	0.1-10 keV	1°	10'' $\Delta t = 10 \mu\text{sec}$	---		70 μJy
FUSE (Lyman)						
Spectrograph	912-1250 Å 300-912 Å	Degrees	---	3×10^4 10^3		mV = 14 - 17
Spectrograph	1250-1700 Å or 1700-3100 Å	Degrees	---	10^4		
Photometer/imager	0.25-0.5 keV		1'	---		10^{-13} erg/cm ² /sec

HST 2nd generation						
Ultraviolet/visible two-dimensional imaging spectrograph	---	---	---	---	---	---
Near-infrared camera and multiobject spectrometer	0.8-2.5 μm	6"X13" or 2"X3"	0.2"X0.2"	2	5X10 ⁻³ -10 ⁻⁸ Jy	
	0.8-2.5 μm	above or 0.2"X13"	0.05"X0.05"	500	10 ⁻⁶ Jy	
	0.8-1.17 μm	5 spots in 4'X4' FOV	0.05"X0.05" 1.8", 1", 0.5", 0.25"	100-1000 10 ⁴	10 ⁻⁵ Jy	
OR						
Imaging Michelson spectrometer	1.0-2.45 μm	10"X10"	0.08"	1-10 ⁴	2X10 ⁻⁸ Jy at 1.6 μm	
	1.0-2 μm (14 1% filters)	40"	0.8"	1-10 ³	2X10 ⁻⁸ Jy at 1.6 μm	

ISO					
Imaging ISOCAM	3-17 μm				50
Spectroscopy SWS LWS ISOPHOT-S	3-50 μm 45-180 μm 3.3-16 μm				10-5X10 ⁴ 200-10 ⁴
Photometry polarimetry ISOPHOT-A ISOPHOT-P ISOPHOT-C	2-18 μm 3-30 μm 30-200 μm				19 broad and narrow spectral bands
SIRTF					
Infrared spectrograph	2.5-4 μm 4-30 μm 30-120 μm 120-200 μm	1.7X17" 6X60" 35"X3' 90"X4.5'	1"7 6" 35" 90"	100 100 2000 100 2000 1000	0.2 mJy 0.3 mJy 4 mJy 1 mJy 8 mJy 10 mJy
Wide-field camera	2-5 μm 5-18 μm 18-30 μm	1.25X1.25 5'X5' 1.25'X1.25' 5'X5' 1.25'X1.25' 5'X5'	0"9 2"3 2"7 4"7 6"6 6"6	3-100	10 ⁻³ mJy 10 ⁻² mJy 5X10 ⁻² mJy

SIRTF						
Multi-imaging photometer	2-7 μm 7-15 μm 15-30 μm 30-60 μm 60-120 μm 120-200 μm 200-400 μm 400-700 μm	30"X30" 30"X30" 30"X30" 30"X30" 5'X5' 15"X120" 5'X5' 5'X5'	1" 3" 6" 12" 24" 44" 80" 150"	3-5		10 ⁻³ mJy 10 ⁻² mJy 5X10 ⁻² mJy 10 ⁻¹ mJy 10 ⁻¹ mJy 1 mJy 10 mJy 10 mJy
FIRST						
Imaging multiband photometer	100-800 μm	---	---	---	---	
High-resolution spectrometer	100-200 μm	---	---	---	10 ⁴	
Very-high-resolution spectrometer	300-650 μm	---	---	---	10 ⁶	
LDR						
Photometric imaging array	1-5 μm 30-120 μm 100-200 μm 100-1000 μm	3'	2" 1.8" 4" 18"	3-100 3-100 3-100 3-100		0.1-10 ⁻⁴ Jy 10 ⁻² Jy 10 ⁻¹ Jy 10 ⁻¹ Jy

LDR					
Medium-resolving-power spectrometer	1-5 μm 5-30 μm 30-120 μm	3'	2" 2" 1.8"	10 ² -10 ³ 10 ² -10 ³ 10 ² -10 ³	10 ⁻³ Jy 10 ⁻¹ Jy 3×10 ⁻² Jy
High-power spectrometer	1-5 μm 30-220 μm	3'	2"	10 ⁴ -10 ⁵ 10 ⁴ -10 ⁵	10 ⁻² Jy 0.1-1 Jy
Ultra-high-resolving-power spectrometer	521-654 μm 361-455 μm 110-157 μm	3'	8" 4" 1.2"	10 ⁶ -10 ⁷ 10 ⁶ -10 ⁷ 10 ⁶ -10 ⁷	3 Jy 6 Jy 3 Jy
KAO					
36-in. telescope on board a C141 75 flights/yr at 40,000-45,000 ft 6 hr/flight	0.8-1500 μm	7'	20" @ 100 μm	10 ⁴ -10 ⁶	1 Jy @ 100 μm (photometric)
3M Balloon					
Dual photometer	30-50 μm 100-300 μm	15' 15'	7" 20"	3-5 3-5	0.15 Jy 0.07-0.2 Jy in 30-min integration

3M Balloon					
Grating spectrometer	30-200 μm	15'	3-16"	30 to 100	
Fourier transform spectrometer	45-200 μm	15'		$10^3 - 10^4$	
Heterodyne	300-1000 μm	15'		$>10^6$	
Anticipated 5 flights/yr and 23 hr/flight					
SOFIA					
3-m telescope on board a 747SP 70 flights/yr at 40,000-45,000 ft 6.5 hr/flight	0.3-1500 μm	8'	7" @ 100 μm	$10^5 - 10^6$	0.1 Jy @ 10 μm (photometric)

Appendix C

CONVERSIONS: WAVELENGTH/FREQUENCY

Domain	Wavelength	Frequency (GHz)
Radio	>1 cm	<30
Millimeter	1-10 mm	300-30
Submillimeter	600-1000 μm	500-300
Far-infrared	2-600 μm	1.5×10^5 -500
Near-infrared	0.7-2 μm	4- 1.5×10^5
Visible	4000-7000 \AA	7.5 - 4×10^5
Ultraviolet	2000-4000 \AA	1.5 - 0.75×10^6
Far-ultraviolet	100-2000 \AA	3 - 0.15×10^7
X-ray	1-100 \AA	3 - 0.03×10^9
Gamma ray	<1 \AA	$>3 \times 10^9$

$$1 \mu\text{m} = 10^{-6} \text{ m}$$

$$1 \text{\AA} = 10^{-8} \text{ m}$$

$$1 \text{ Hz} = 1 \text{ cycle/sec}$$

$$1 \text{ GHz} = 10^9 \text{ Hz}$$

$$1 \text{ Jy} = 10^{-26} \text{ W/m}^2/\text{Hz}$$

$$\log [f_{\nu} \text{ (in Jy)}] = -0.4 m_{\nu} + 3.57$$

$$m_{\nu} = 20 \text{ is equivalent to } f_{\nu} = 4 \times 10^{-5} \text{ Jy}$$

Appendix D

CONVERSIONS: LINEAR SIZE/ANGULAR SIZE

Domain	Linear size	Distance	Angular size
Moon, diameter	3476 km	0.00257 AU	31.09'
Mars	6786 km	0.524 AU	17.9"
10 km at Mars	10 km	0.524 AU	0.0263"
Sun	1 391 980 km	1 AU	31.99'
Ceres	772 km	1.892 AU	0.563"
Jupiter	142 796 km	4.203 AU	46.9"
Io	3630 km	4.203 AU	1.19"
Europa	3138 km	4.203 AU	1.03"
Great Red Spot	24 000 km	4.203 AU	7.88"
	X 15 000 km		X 4.92"
10 km at Jupiter	10 km	4.203 AU	0.0033"
Saturn	120 660 km	8.555 AU	19.5"
Titan (visible cloud layer)	5550 km	8.555 AU	0.895"
Iapetus	1460 km	8.555 AU	0.118"
Phoebe	220 km	8.555 AU	0.036"
Uranus	51 200 km	18.218 AU	3.9"
Neptune	50 460 km	29.110 AU	2.4"
Pluto	3400 km	38.44 AU	0.12"
Earth-Sun orbit, radius	1 AU	1 pc	1"
		(nearest star)	
		160 pc	0.0062"
		(nearest star formation)	
Jupiter-Sun orbit	5.20 AU	1 pc	5.2"
Solar System diameter	~100 AU	1 pc	1.67'
		160 pc	0.625"
1 solar mass protostar core	6×10^5 km	160 pc	0.025 mas
Accretion Disk around 1 solar mass protostar	2×10^9 km	160 pc	0.08"
		10 kpc	1.28 mas
		(to galactic center)	

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Domain	Linear size	Distance	Angular size
Dusty Envelope around 1 solar mass protostar	2×10^{12} km	160 pc	1.33'
		10 kpc	1.28''
Diffuse Molecular Cloud	1 pc	100 pc	34.38'
		1 kpc	3.44'
		10 kpc	20.6''
		30 kpc	6.8''
		(across Milky Way)	
		1 Mpc	0.206''
		(nearest galaxy)	
Giant Molecular Cloud	5 pc	1 kpc	17.19'
		10 kpc	1.719'
		30 kpc	34.38''
		1 Mpc	1.03''
Giant Molecular Cloud Core	0.1 pc	1 kpc	20.62''
		10 kpc	2.06''
		30 kpc	0.688''
		1 Mpc	20.62 mas
Compact HII Region	0.01 pc	100 pc	20.62''
		1 kpc	2.06''
		10 kpc	0.206''
		30 kpc	68.67 mas
		1 Mpc	2.06 mas
HII Region Complex	2 pc	1 kpc	6.87'
		10 kpc	41.25''
		30 kpc	13.75''
		1 Mpc	0.412''

